Cosmic-ray Electron and Positron Spectrum from CALET Observations on ISS

Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University

CALET Collaboration Team

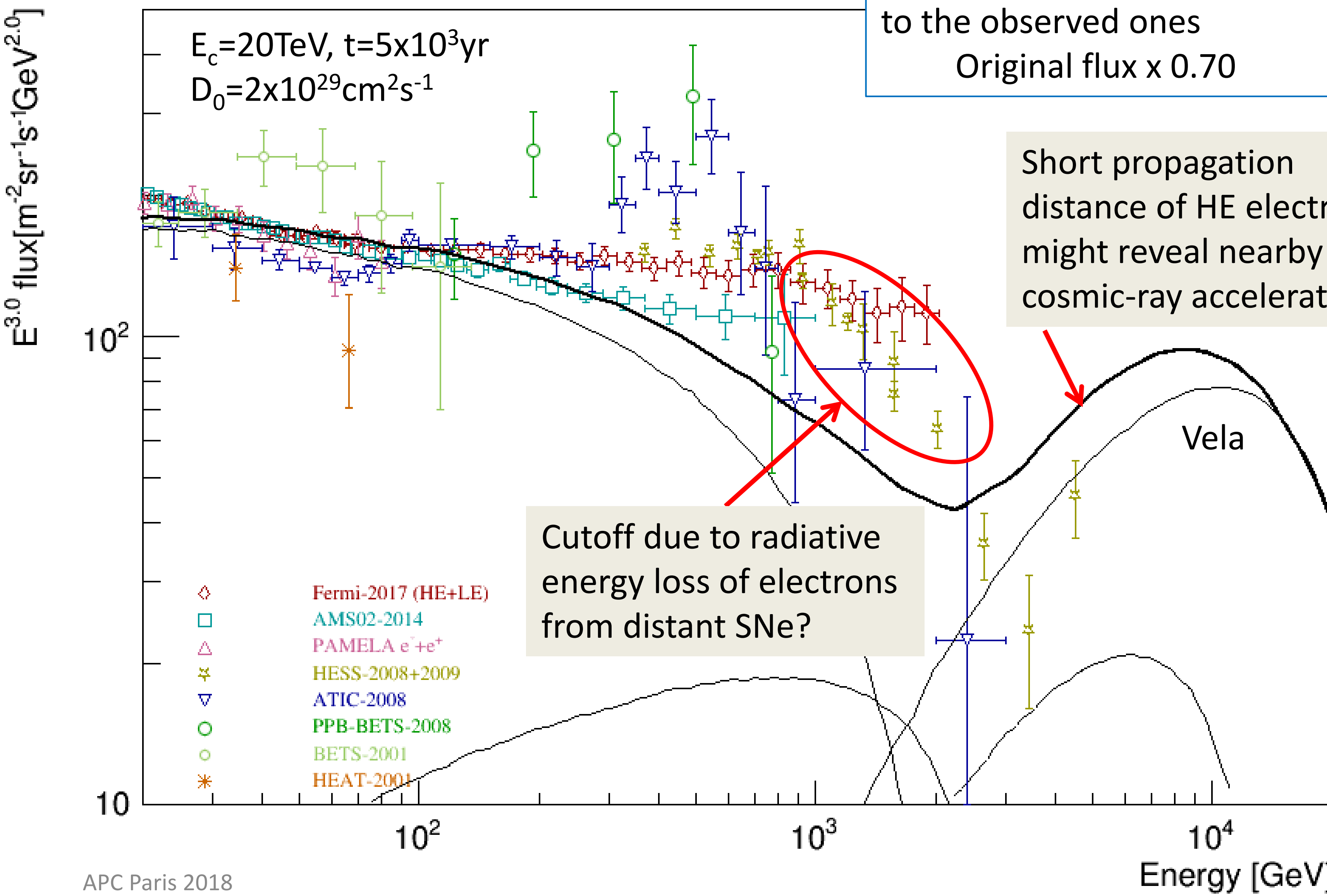
O. Adriani[25], Y. Akaike[2], K. Asano[7], Y. Asaoka[9,31], M.G. Bagliesi[29], E. Berti[25], G. Bigongiari[29], W.R. Binns[32], S. Bonechi[29], M. Bongi[25], P. Brogi[29], A. Bruno[15], J.H. Buckley[32], N. Cannady[13], G. Castellini[25], C. Checchia[26],M.L. Cherry[13], G. Collazuol[26], V. Di Felice[28], K. Ebisawa[8], H. Fuke[8], T.G. Guzik[13], T. Hams[3], N. Hasebe[31], K. Hibino[10], M. Ichimura[4], K. Ioka[34], W. Ishizaki[7], M.H. Israel[32], K. Kasahara[31], J. Kataoka[31], R. Kataoka[17], Y. Katayose[33], C. Kato[23], Y.Kawakubo[1], N. Kawanaka[30], K. Kohri [12], H.S. Krawczynski[32], J.F. Krizmanic[2], T. Lomtadze[27], P. Maestro[29], P.S. Marrocchesi[29], A.M. Messineo[27], J.W. Mitchell[15], S. Miyake[5], A.A. Moiseev[3], K. Mori[9,31], M. Mori[21], N. Mori[25], H.M. Motz[31], K. Munakata[23], H. Murakami[31], S. Nakahira[20], J. Nishimura[8], G.A De Nolfo[15], S. Okuno[10], J.F. Ormes[25], S. Ozawa[31], L. Pacini[25], F. Palma[28], V. Pal'shin[1], P. Papini[25], A.V. Penacchioni[29], B.F. Rauch[32], S.B. Ricciarini[25], K. Sakai[3], T. Sakamoto[1], M. Sasaki[3], Y. Shimizu[10], A. Shiomi[18], R. Sparvoli[28], P. Spillantini[25], F. Stolzi[29], S. Sugita[1], J.E. Suh[29], A. Sulaj[29], I. Takahashi[11], M. Takayanagi[8], M. Takita[7], T. Tamura[10], N. Tateyama[10], T. Terasawa[7], H. Tomida[8], S. Torii[9,31], Y. Tunesada[19], Y. Uchihori[16], S. Ueno[8], E. Vannuccini[25], J.P. Wefel[13], K. Yamaoka[14], S. Yanagita[6], A. Yoshida[1], and K. Yoshida[22]

1) Aoyama Gakuin University, Japan
2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
4) Hirosaki University, Japan
5) Ibaraki National College of Technology, Japan
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
17) National Institute of Polar Research, Japan
18) Nihon University, Japan
19) Osaka City University, Japan
20) RIKEN, Japan
21) Ritsumeikan University, Japan
22) Shibaura Institute of Technology, Japan
23) Shinshu University, Japan
24) University of Denver, USA
25) University of Florence, IFAC (CNR) and INFN, Italy
26) University of Padova and INFN, Italy
27) University of Pisa and INFN, Italy
28) University of Rome Tor Vergata and INFN, Italy
29) University of Siena and INFN, Italy
30) University of Tokyo, Japan
31) Waseda University, Japan
32) Washington University-St. Louis, USA
33) Yokohama National University, Japan
34) Yukawa Institute for Theoretical Physics, Kyoto University, Japan

Cosmic-Ray All-Electron Spectrum (e^++e^-)

Kobayashi et al. ApJ 2004

Calculated results normalized to the observed ones
Original flux x 0.70

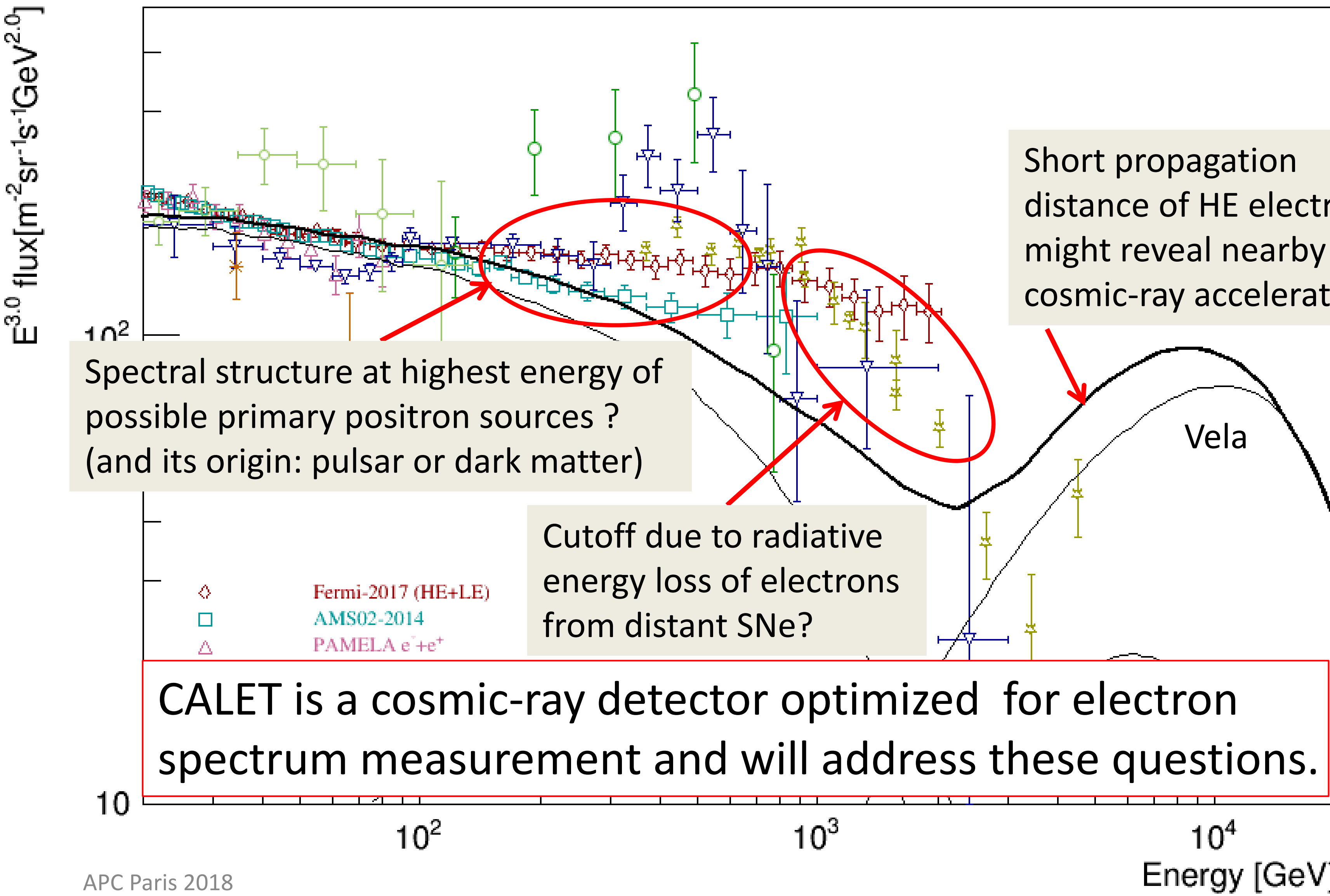


Short propagation distance of HE electrons might reveal nearby cosmic-ray accelerator!

Cutoff due to radiative energy loss of electrons from distant SNe?

Cosmic-Ray All-Electron Spectrum ($e^{+}+e^{-}$)

Possible fine structures in all-electron (electron + positron) spectrum



Short propagation distance of HE electrons might reveal nearby cosmic-ray accelerator!

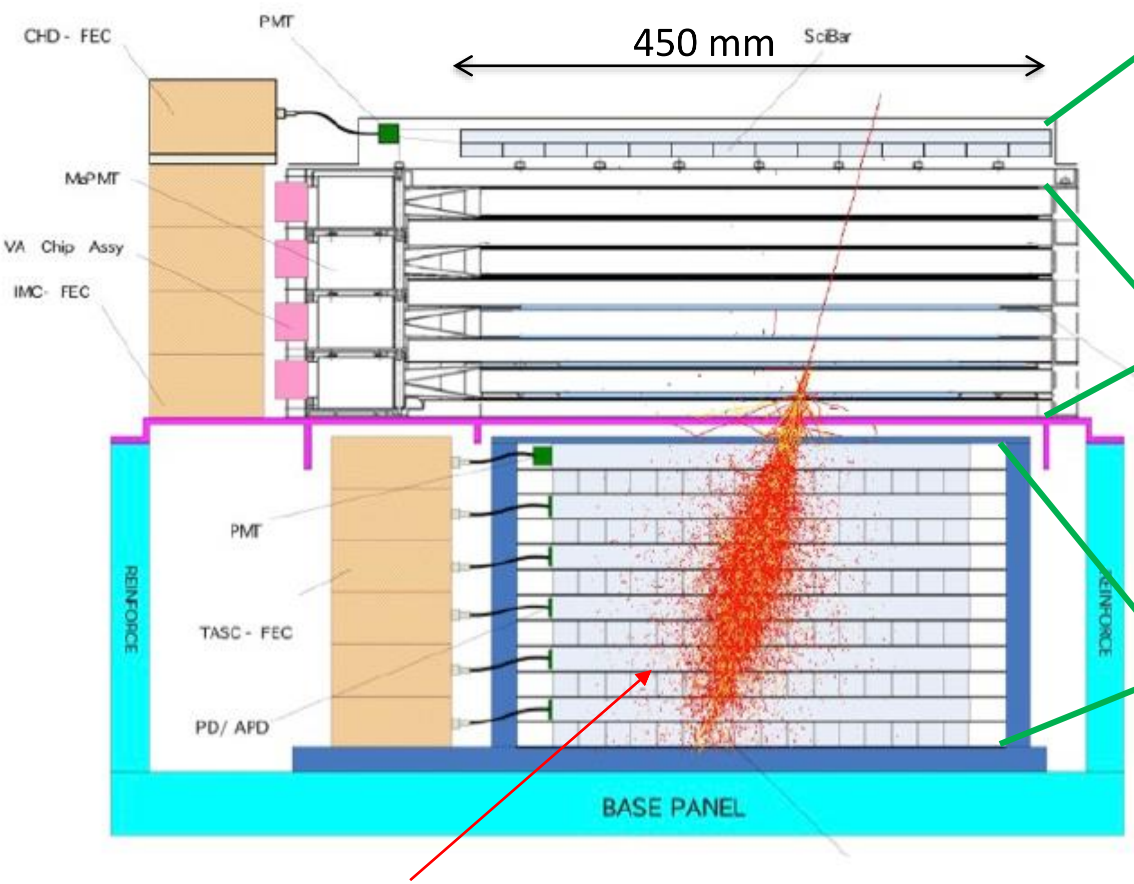
Spectral structure at highest energy of possible primary positron sources ? (and its origin: pulsar or dark matter)

Cutoff due to radiative energy loss of electrons from distant SNe?

CALET is a cosmic-ray detector optimized for electron spectrum measurement and will address these questions.

CALET-CAL Detector

Fully active thick calorimeter ($30X_0$) optimized for electron spectrum measurements well into the TeV region



Charge Detector **CHD**

plastic scintillator hodoscope,
absolute charge measurement
(including charge zero)

Imaging Calorimeter **IMC**

SciFi + tungsten plate ($3X_0$),
reconstruction of shower axis and initial shower development

Total Absorption Calorimeter **TASC**

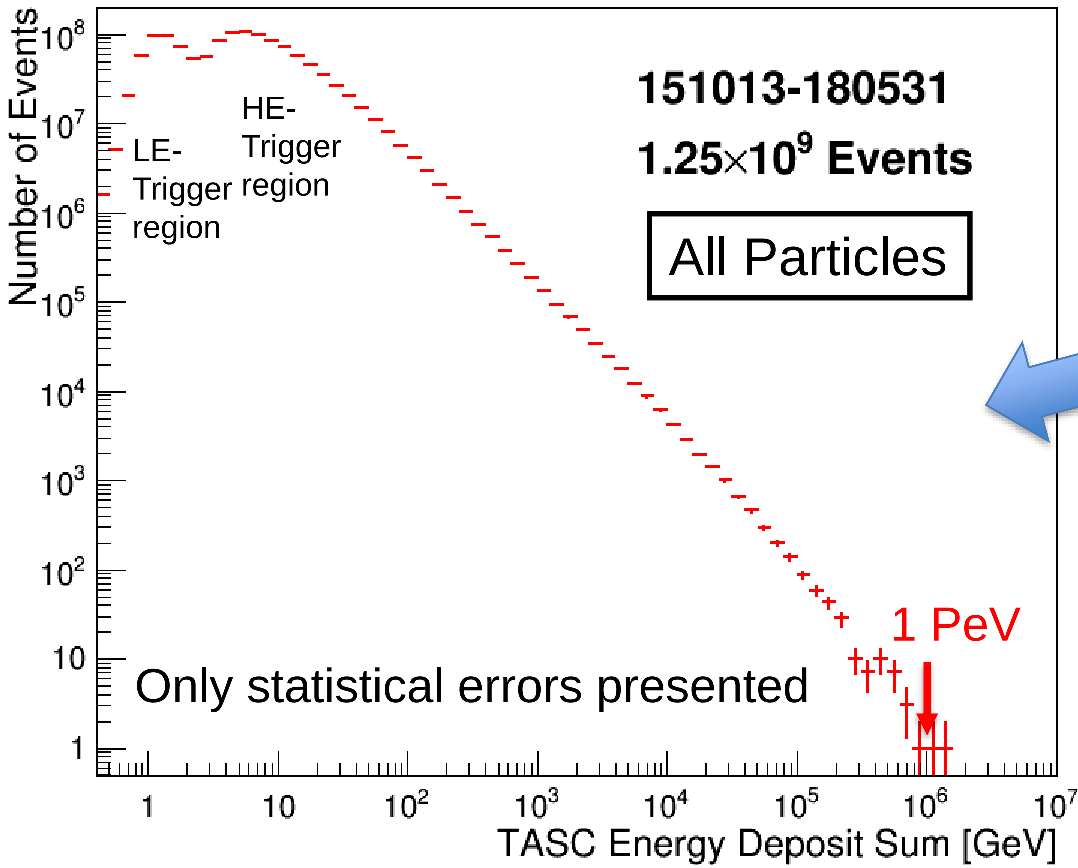
PWO hodoscope (27X0),
energy measurements and particle identification

1TeV electron shower is fully contained in TASC
(95% of primary electron energy is actually measured by TASC)

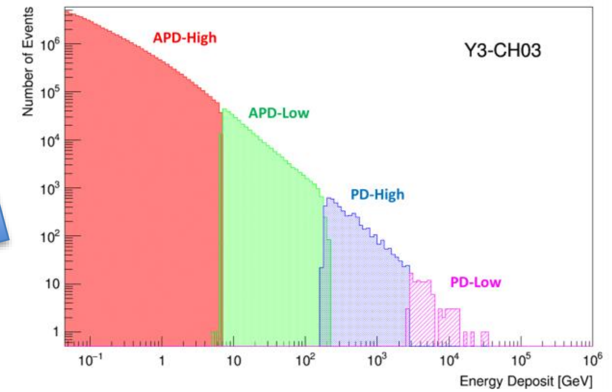
Wide Dynamic Range Energy Measurement with TASC

Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.

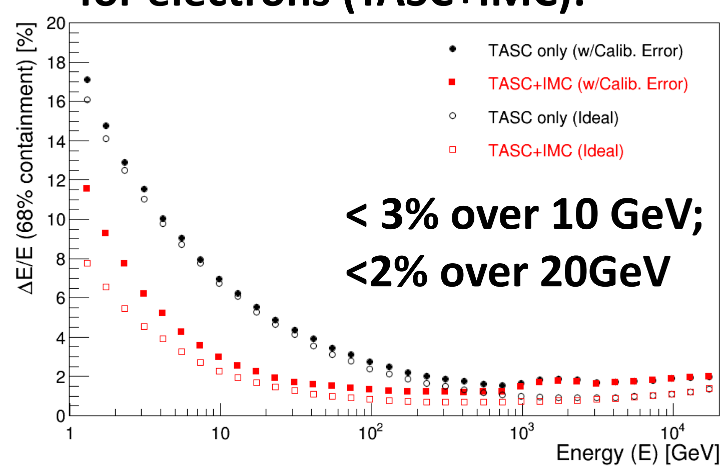
Distribution of deposit energies (ΔE) in TASC



Example of energy distribution in one PWO log



Energy resolution for electrons (TASC+IMC):



The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

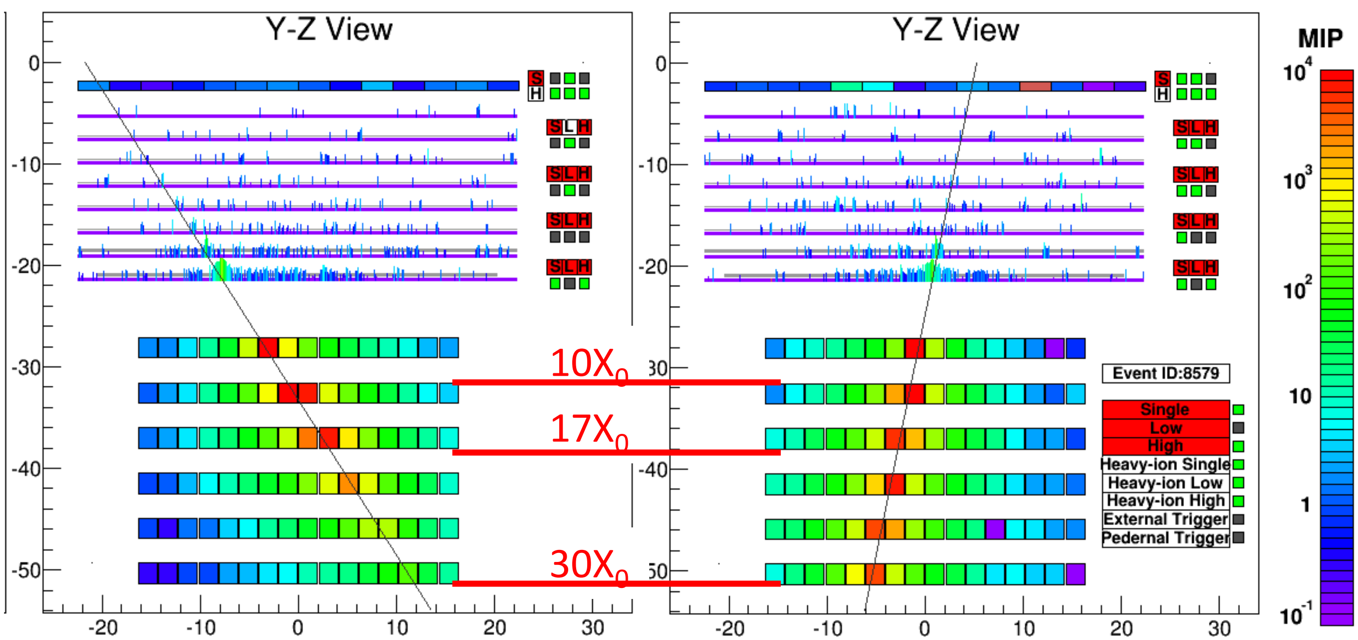
All-Electron (electron + positron) Analysis

CALET is an instrument optimized for all-electron spectrum measurements.

⇒ CALET is best suited for observation of possible fine structures in the all-electron spectrum up to the trans-TeV region.

3TeV Electron Candidate

Corresponding Proton Background



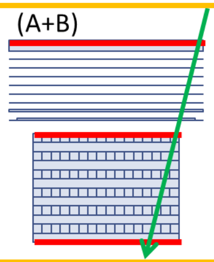
(Flight data; detector size in cm)

1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ thickness, closely packed logs

Event Selection

Analyzed Flight Data:

- 627 days (October 13, 2015 to June 30, 2017)
- 55% of full CALET acceptance (Acceptance A+B; 570cm^{2}sr)

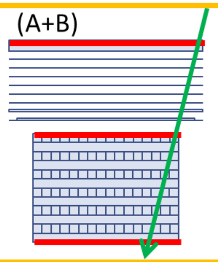


1. Offline Trigger
2. Acceptance Cut
3. Single Charge Selection
4. Track Quality Cut
5. Shower Development Consistency
6. Electron Identification
    1. Simple two parameter cut
    2. Multivariate Analysis using Boosted Decision Trees (BDT)

Event Selection

Analyzed Flight Data:

- 627 days (October 13, 2015 to June 30, 2017)
- 55% of full CALET acceptance (Acceptance A+B; 570cm^{2}sr)



1. Offline Trigger
2. Acceptance Cut
3. Single Charge Selection
4. Track Quality Cut
5. Shower Development Consistency
6. Electron Identification
    1. Simple two parameter cut
    2. Multivariate Analysis using Boosted Decision Trees (BDT)

Pre-selection:

- Select events with successful reconstructions
- Rejecting heavier particles
- Equivalent sample between flight and MC data

Electron Identification

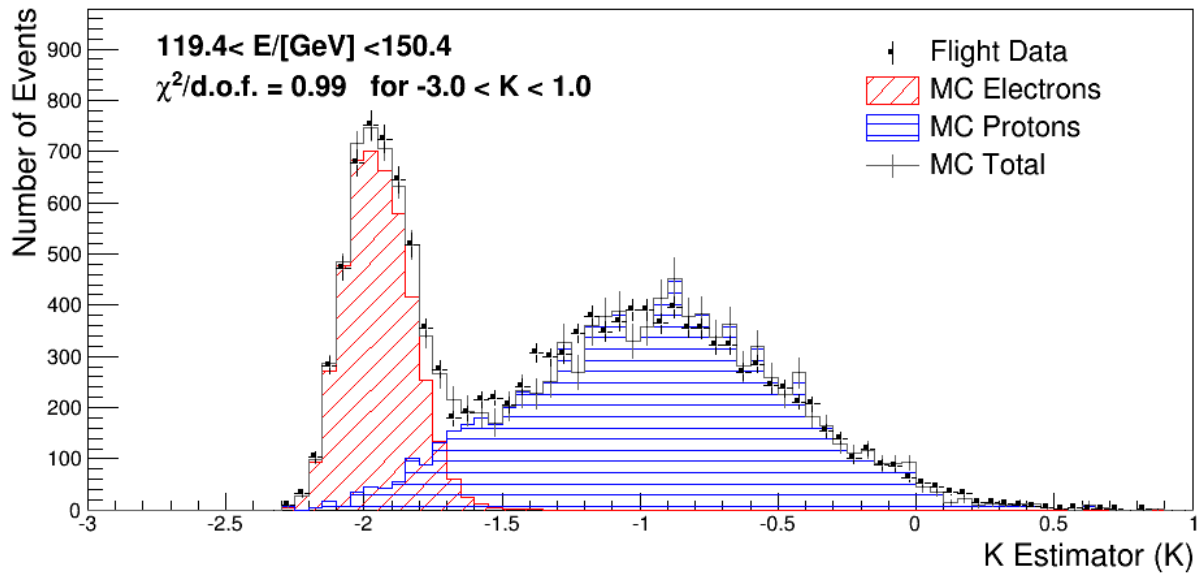
Simple Two Parameter Cut

F_E: Energy fraction of the bottom layer sum to the whole energy deposit sum in TASC

R_E: Lateral spread of energy deposit in TASC-X1

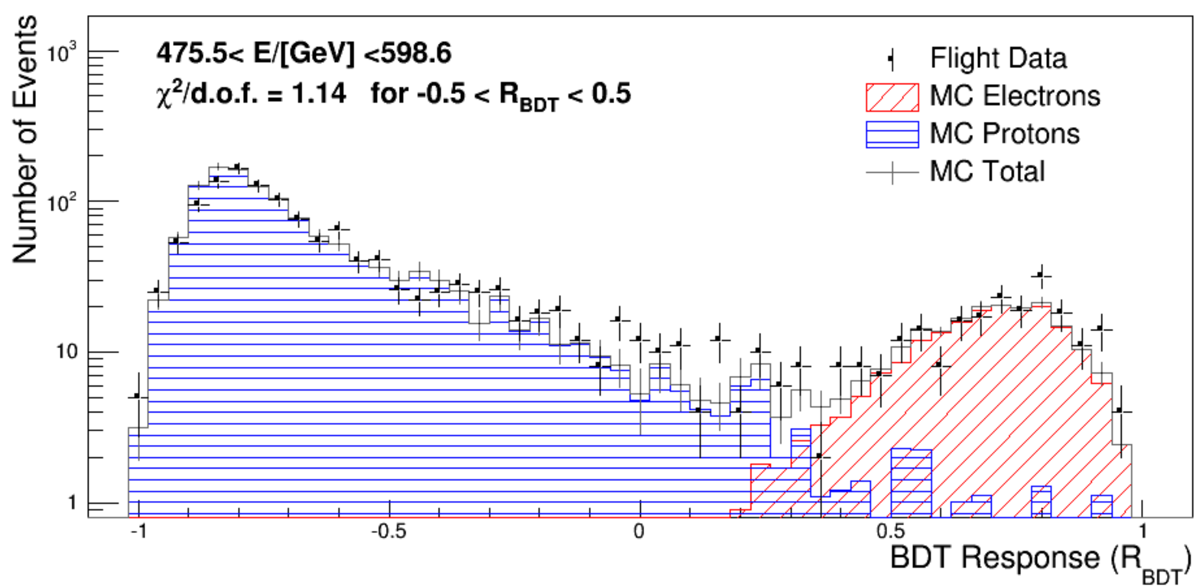
Separation Parameter K is defined as follows:

$$K = \log_{10}(F_E) + 0.5\, R_E\ (/\mathrm{cm})$$

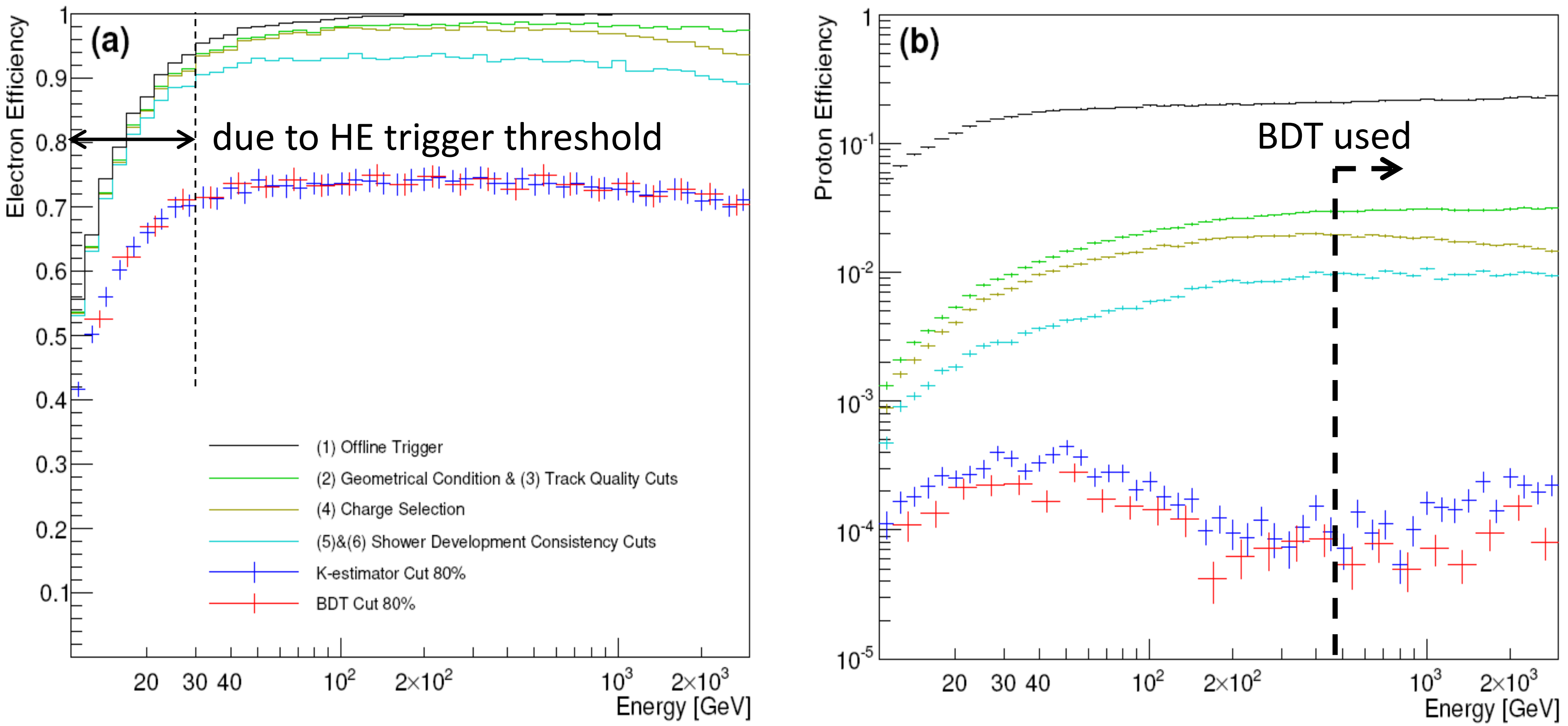


Boosted Decision Trees

In addition to the two parameters making up K, TASC and IMC shower profile fits are used as discriminating variables.

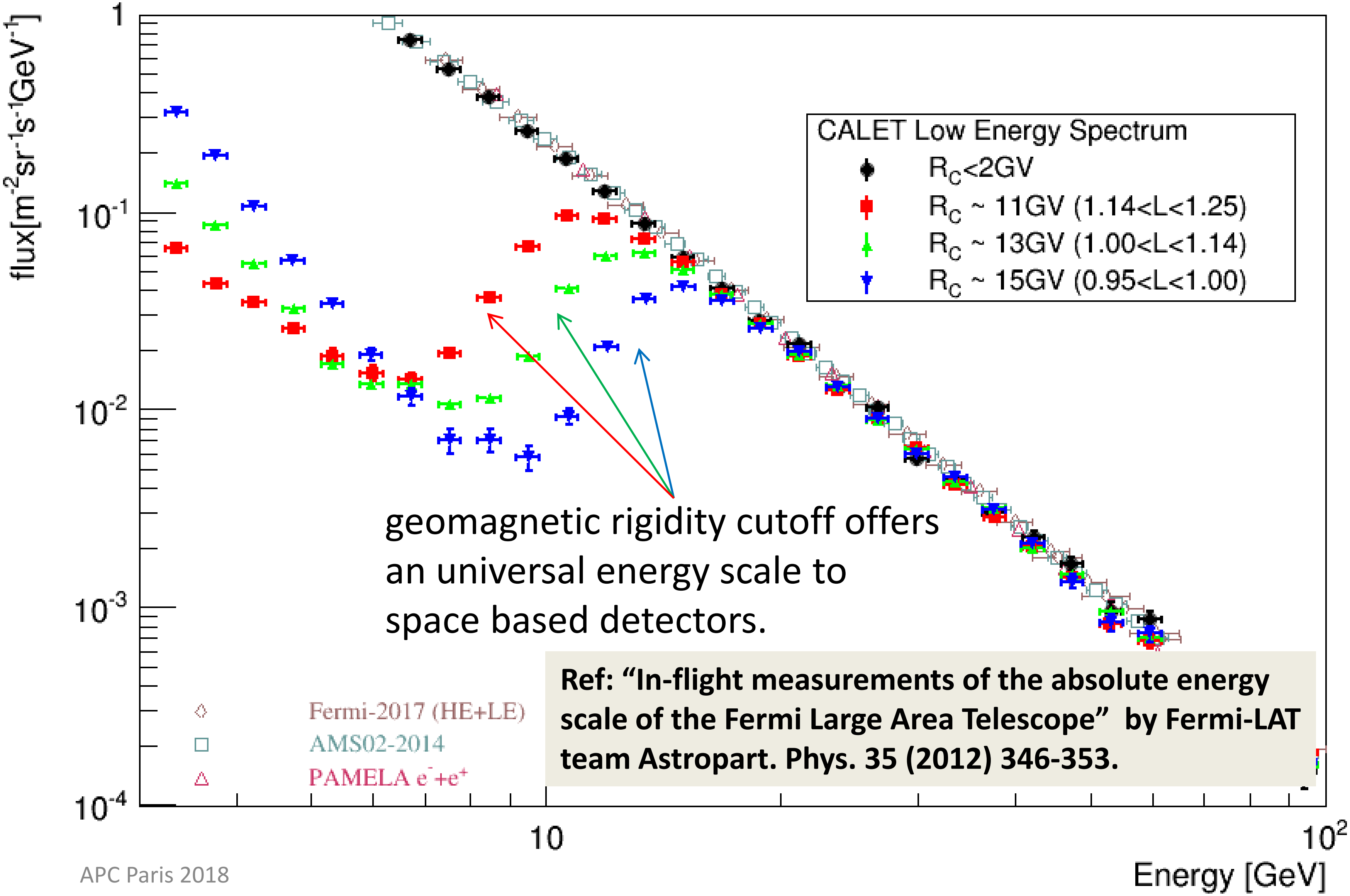


Electron Efficiency and Proton Rejection



- Constant and high efficiency is the key point in our analysis.
- Simple two parameter (BDT) cut is used in the energy region E<475GeV (E>475GeV) while the small difference in resultant spectrum between two methods are taken into account in the systematic uncertainty.
- Contamination is ~5% up to 1TeV, and <15% in the 1—3 TeV region.

Absolute Calibration of Energy Scale using Geomagnetic Rigidity Cutoff

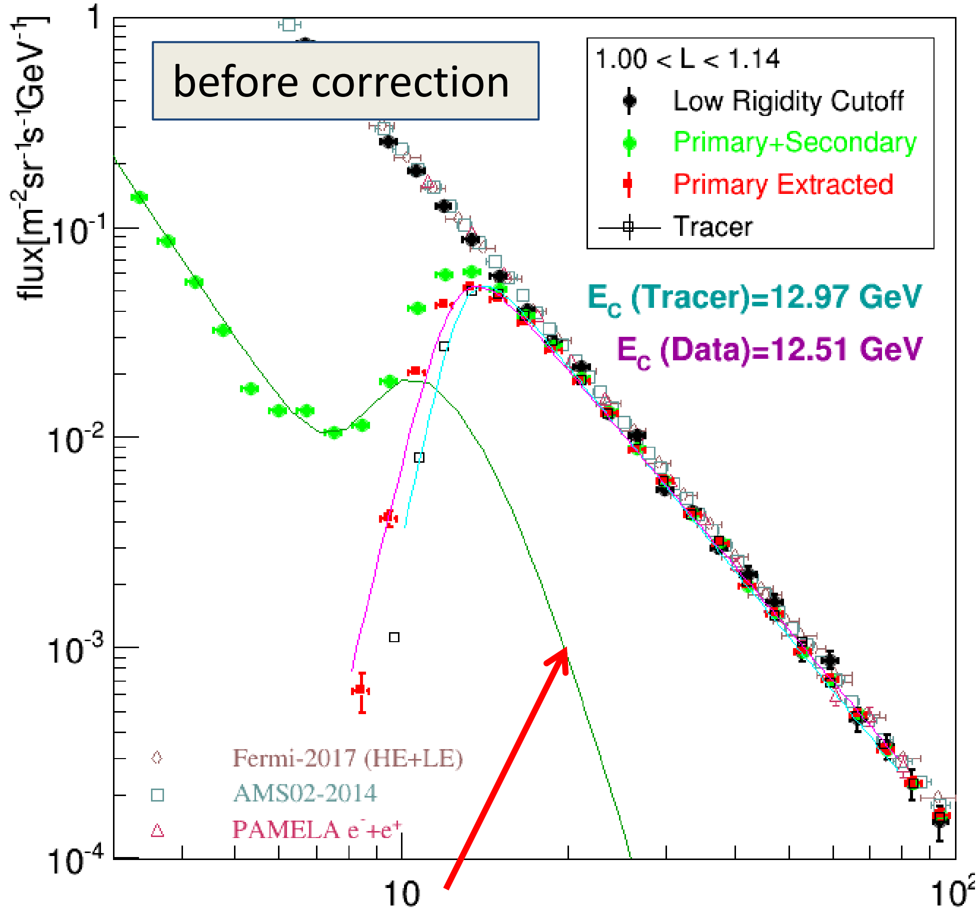


geomagnetic rigidity cutoff offers an universal energy scale to space based detectors.

Ref: "In-flight measurements of the absolute energy scale of the Fermi Large Area Telescope" by Fermi-LAT team Astropart. Phys. 35 (2012) 346-353.

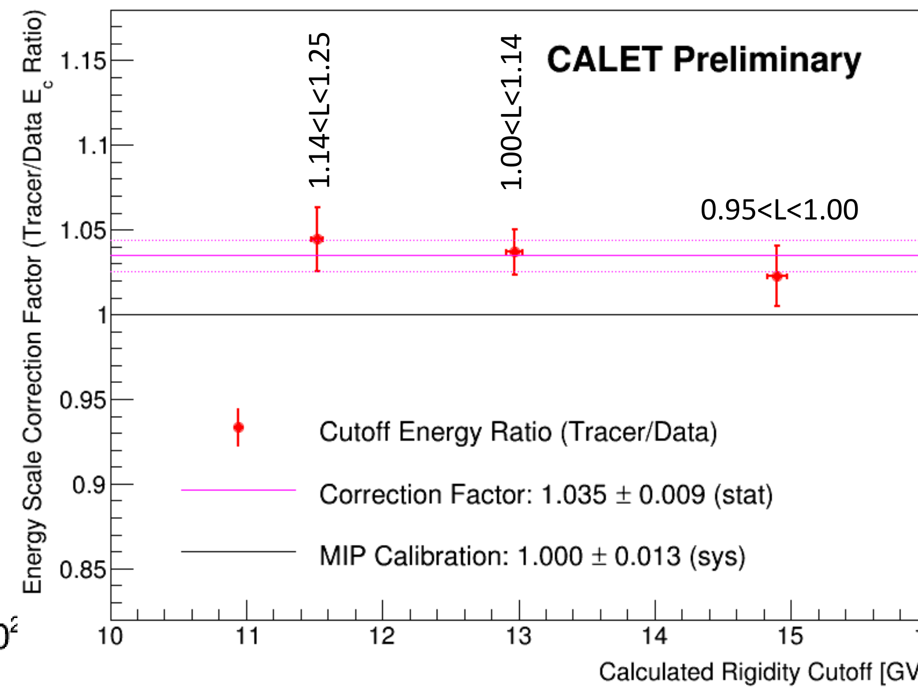
Cutoff Rigidity Measurements and Comparison with Calculation

Measured cutoff rigidity is compared with calculated one (denoted as Tracer) which trace particle in earth's magnetic field (IGRF12).



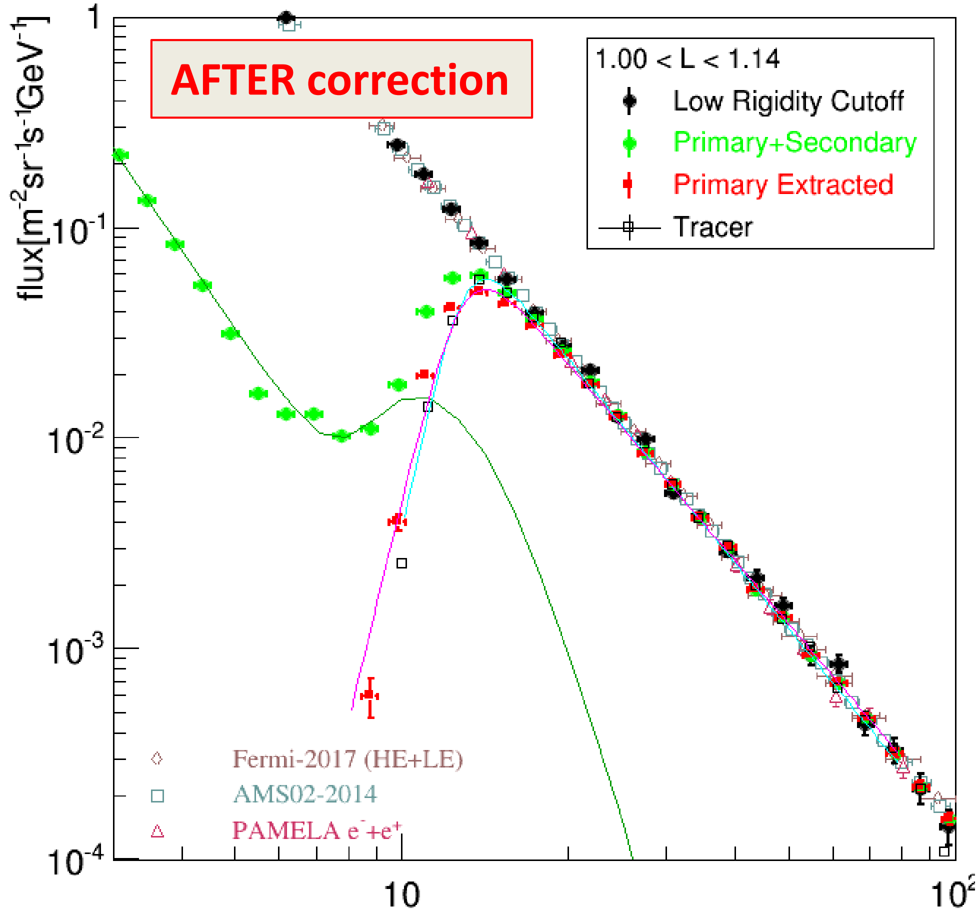
Secondary component is estimated using azimuthal distributions

- Same analysis performed in 3 different rigidity cutoff regions.



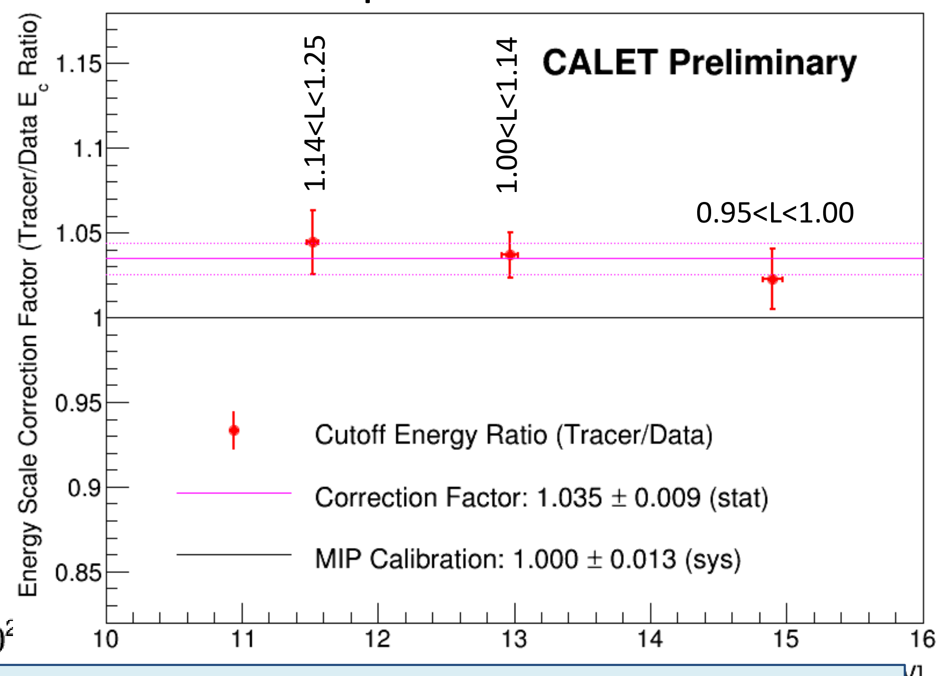
Cutoff Rigidity Measurements and Comparison with Calculation

Measured cutoff rigidity is compared with calculated one (denoted as Tracer) which trace particle in earth's magnetic field (IGRF12).



- Same analysis performed in 3 different rigidity cutoff regions.

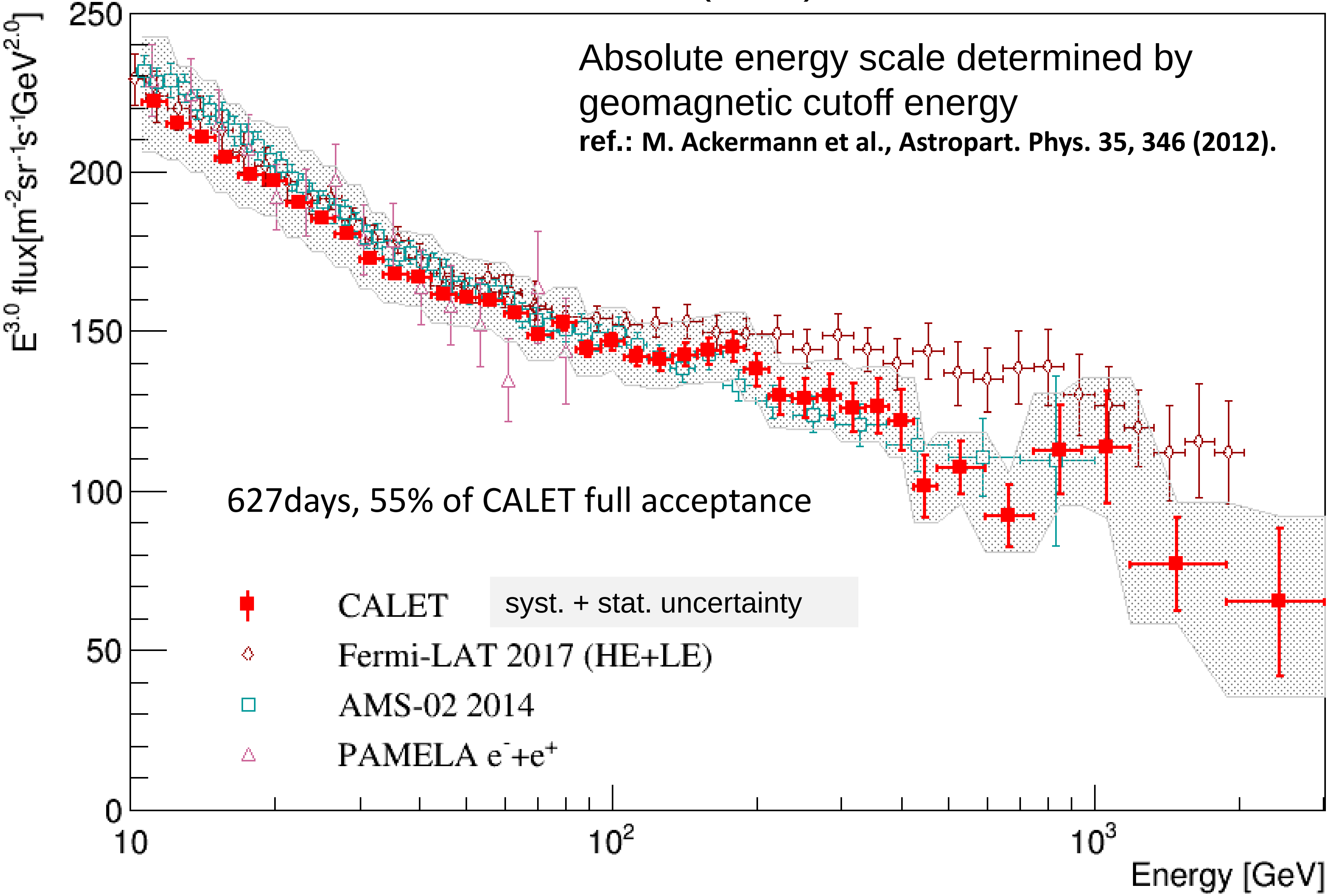
⇒ Correction factor was found to be **1.035** compared to MIP calibration.



Since universal energy-scale calibration between different instruments is very important, we adopt the energy scale determined by rigidity cutoff to derive our spectrum.

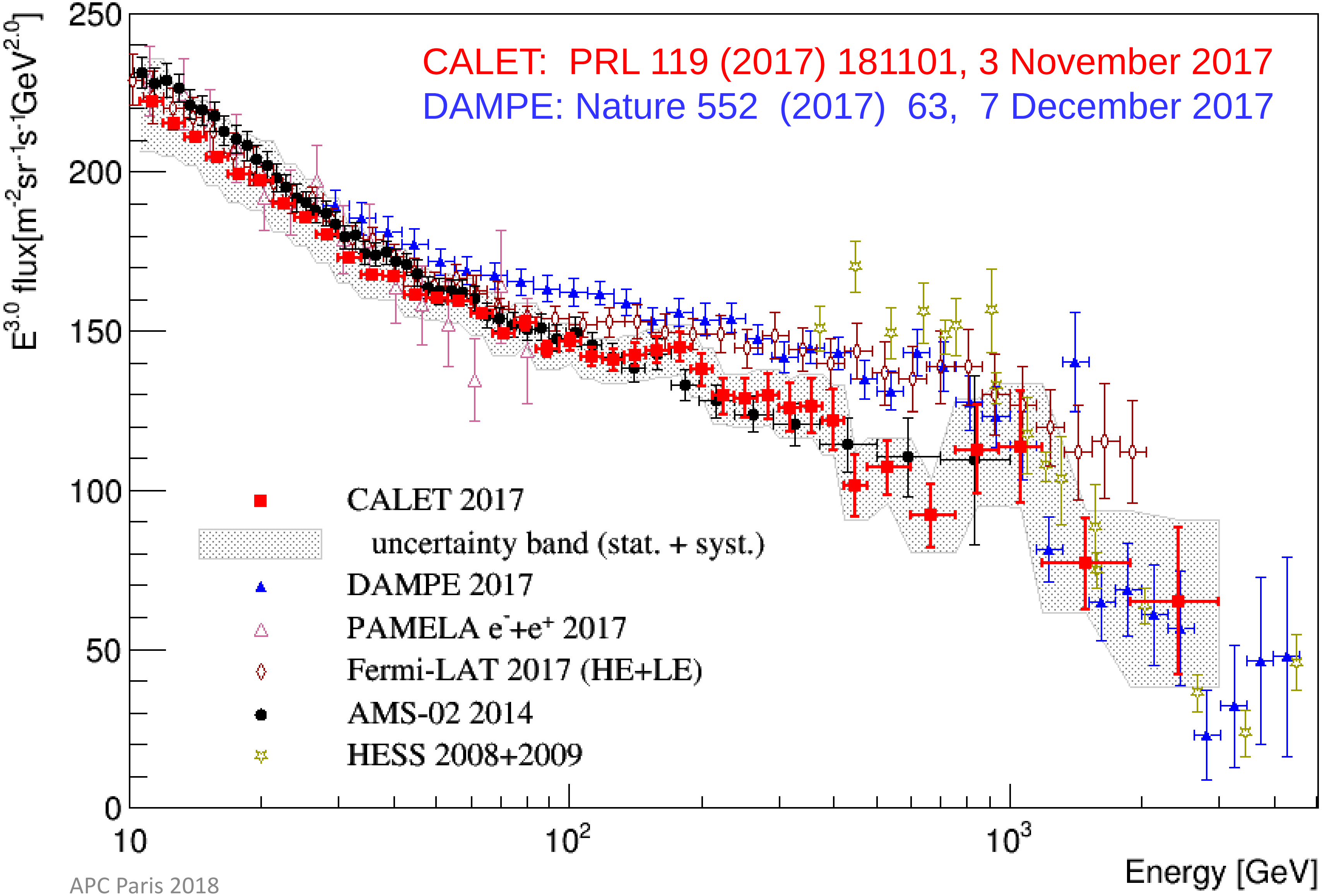
All-Electron Spectrum Measured with CALET from 10 GeV to 3 TeV

CALET: PRL 119 (2017) 181101, 3 November 2017



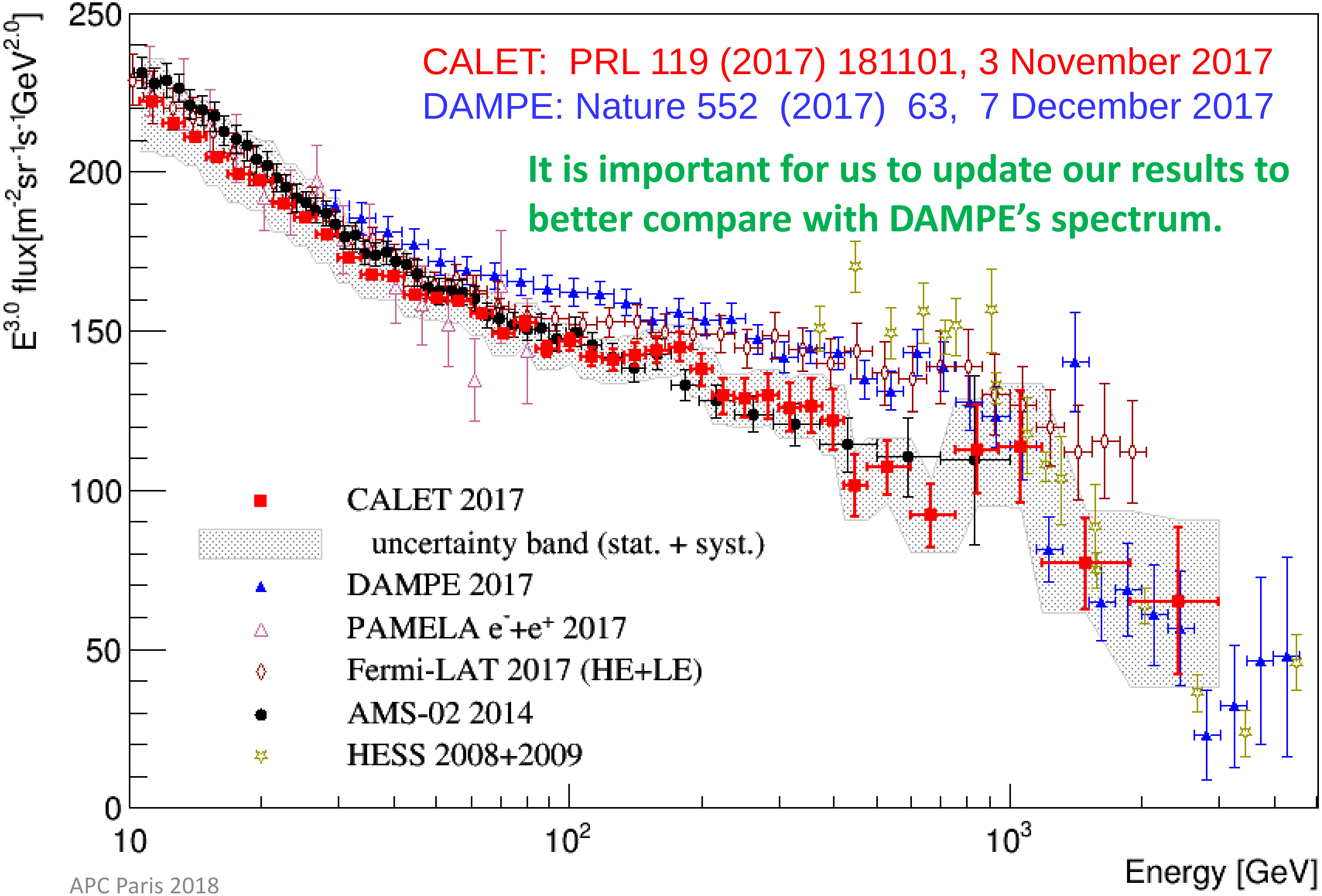
All-Electron Spectrum Comparison w/ DAMPE

and other space based experiments



All-Electron Spectrum Comparison w/ DAMPE

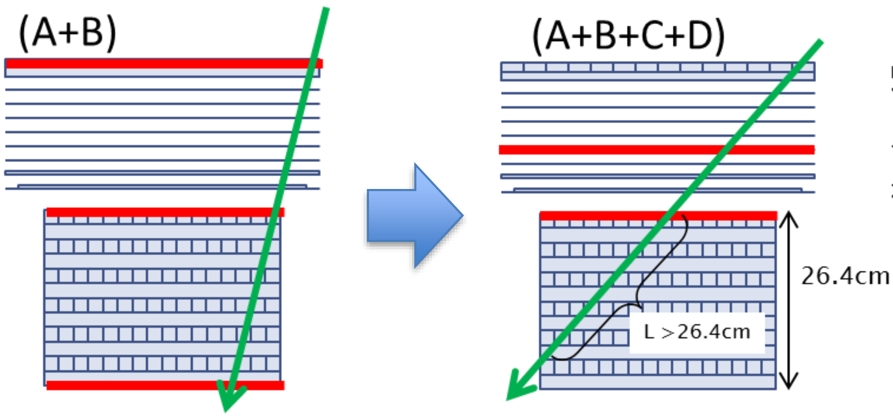
and other space based experiments

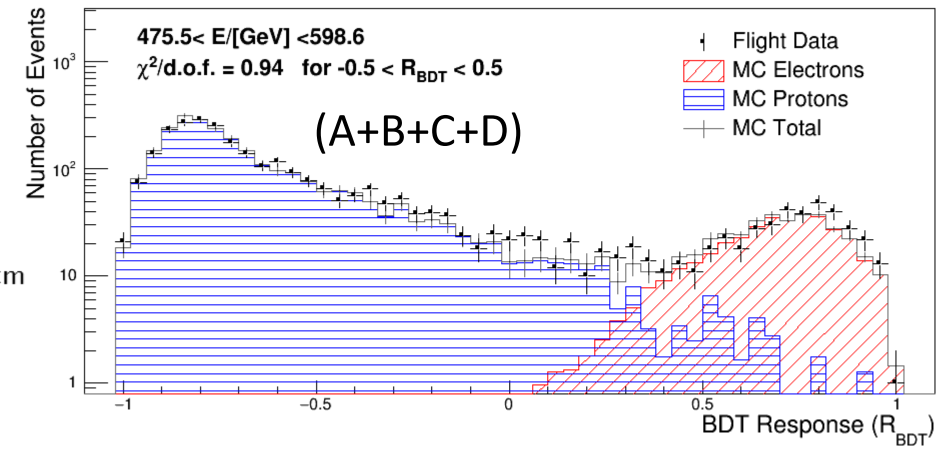


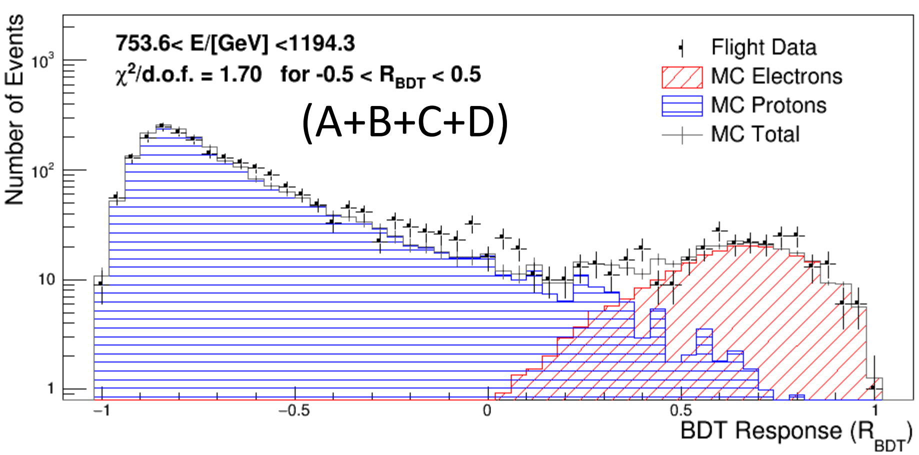
Extending the Analysis to Full Acceptance

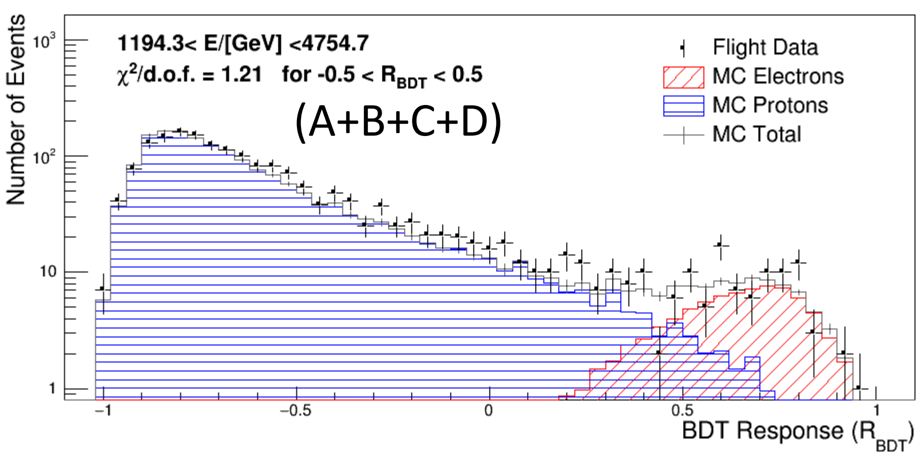
Analyzed Flight Data:

- 780 days (October 13, 2015 to November 30, 2017)
- Full CALET acceptance at the high energy region (Acceptance A+B+C+D; 1040cm^{2}sr). In the low energy region fully contained events are used (A+B; 550cm^{2}sr)









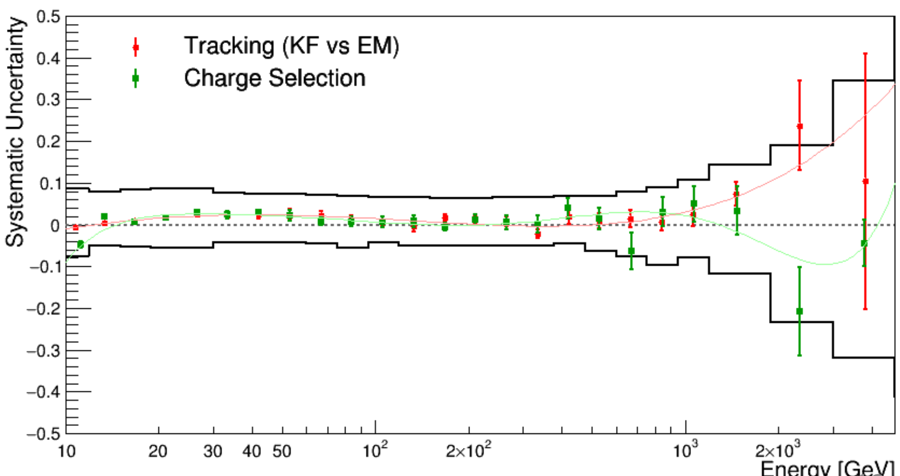
Systematic Uncertainties

(other than energy scale uncertainty)

The energy scale uncertainty does not have energy dependence, because of the full containment of the EM showers well into the TeV region. Errors due to calibration of lower gain ranges are found to be negligible.

Stability of resultant flux are analyzed by scanning parameter space

- Normalization:
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts
- Energy dependent:
  - 2 independent tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - **BDT stability** (vs efficiency & training)
  - MC model (EPICS vs Geant4)



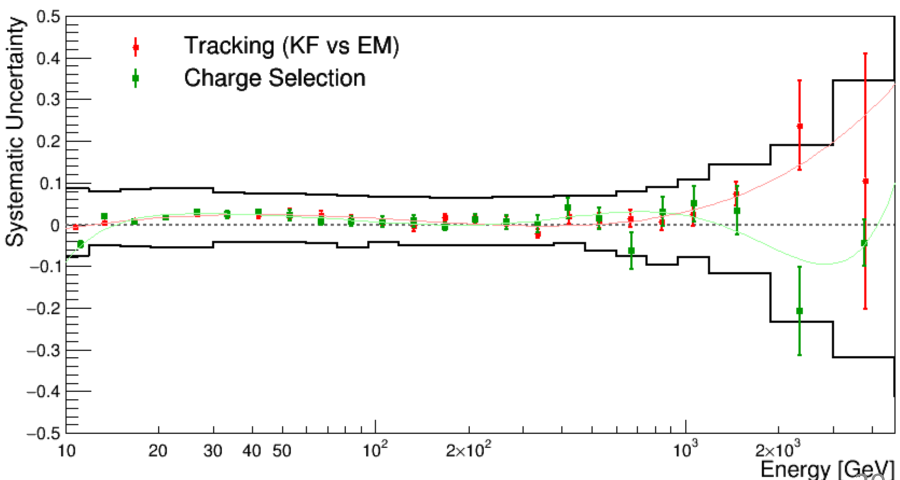
Systematic Uncertainties

(other than energy scale uncertainty)

Stability of resultant flux are analyzed by scanning parameter space

- Normalization:
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts
- Energy dependent:
  - 2 independent tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - **BDT stability** (vs efficiency & training)
  - MC model (EPICS vs Geant4)

1. Divided into 4 sub-periods (195days each)
2. spectrum in each sub-period is compared with the one from the whole period.
3. standard deviation of the relative difference distribution is taken as systematic uncertainty (1.4%)



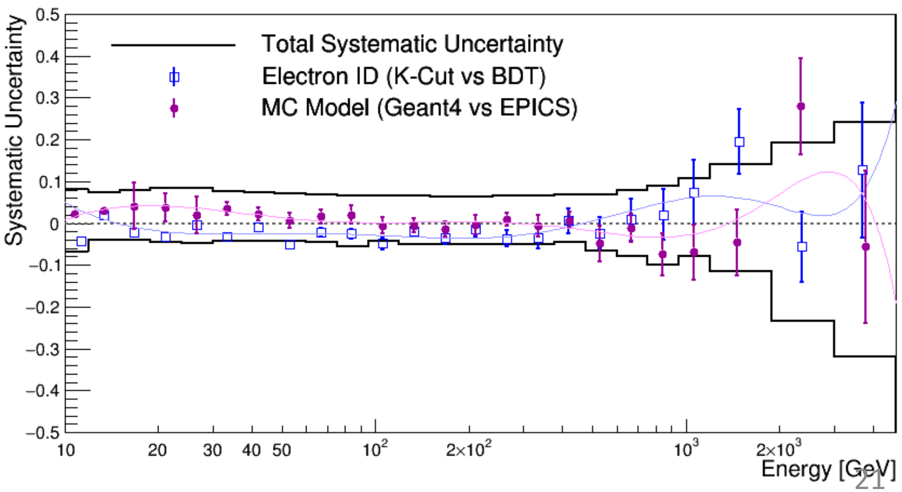
Systematic Uncertainties

(other than energy scale uncertainty)

Stability of resultant flux are analyzed by scanning parameter space

- Normalization:
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts
- Energy dependent:
  - 2 independent tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - **BDT stability** (vs efficiency & training)
  - MC model (EPICS vs Geant4)

1. Divided into 4 sub-periods (195days each)
2. spectrum in each sub-period is compared with the one from the whole period.
3. standard deviation of the relative difference distribution is taken as systematic uncertainty (1.4%)



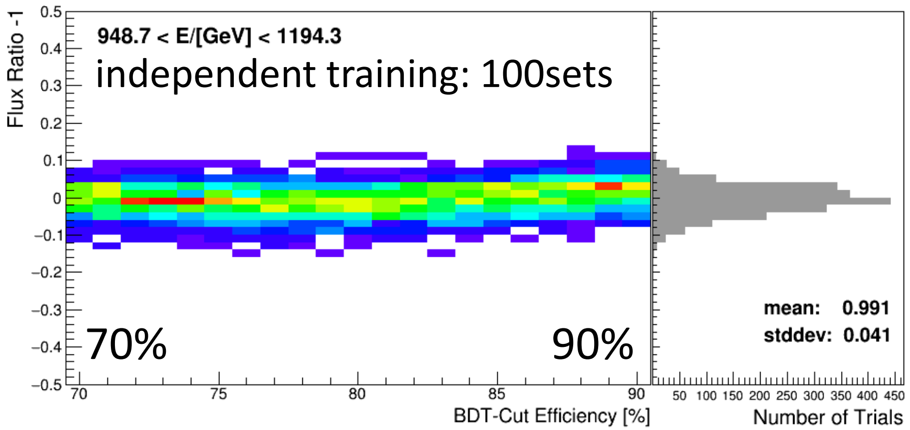
Systematic Uncertainties

(other than energy scale uncertainty)

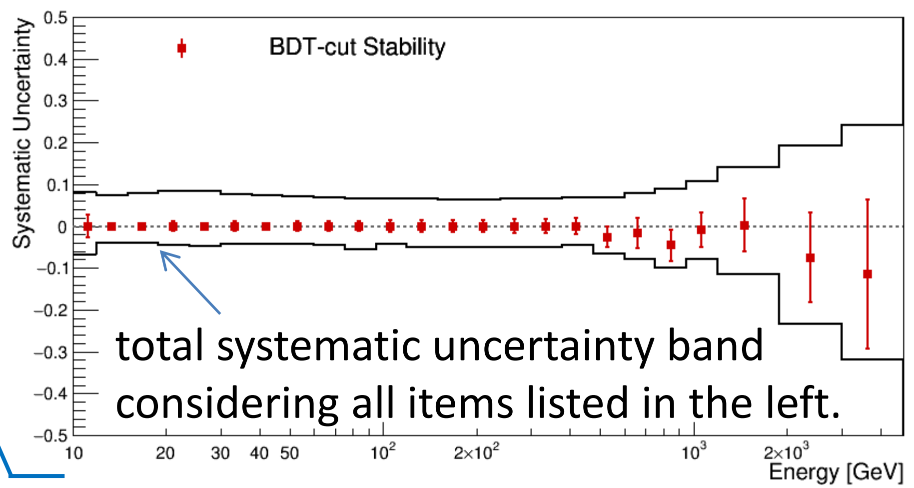
Stability of resultant flux are analyzed by scanning parameter space

- Normalization:
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts
- Energy dependent:
  - 2 independent tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - **BDT stability** (vs efficiency & training)
  - MC model (EPICS vs Geant4)

Flux Ratio vs Efficiency for BDT @ 1TeV

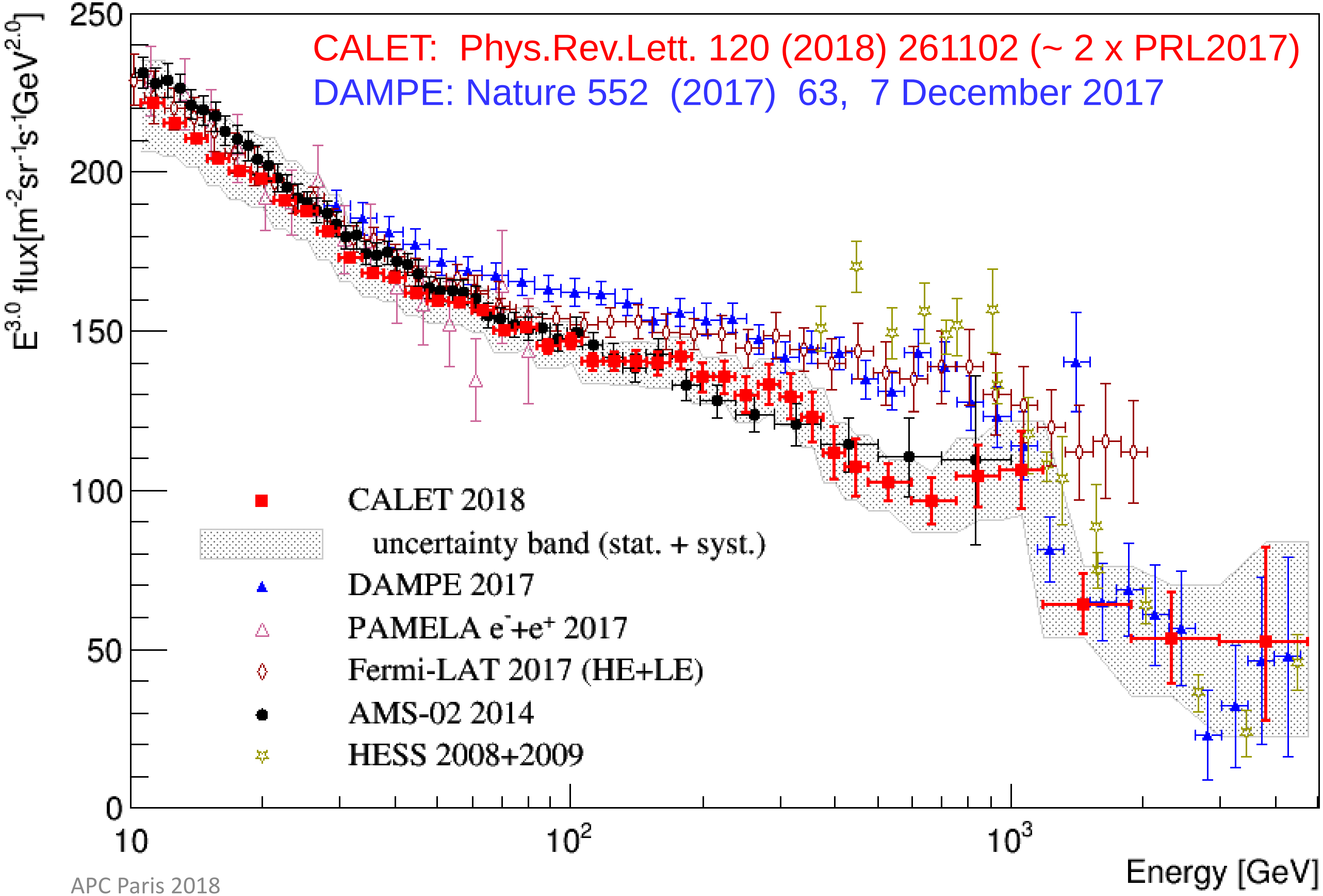


Energy Dependence of BDT stability



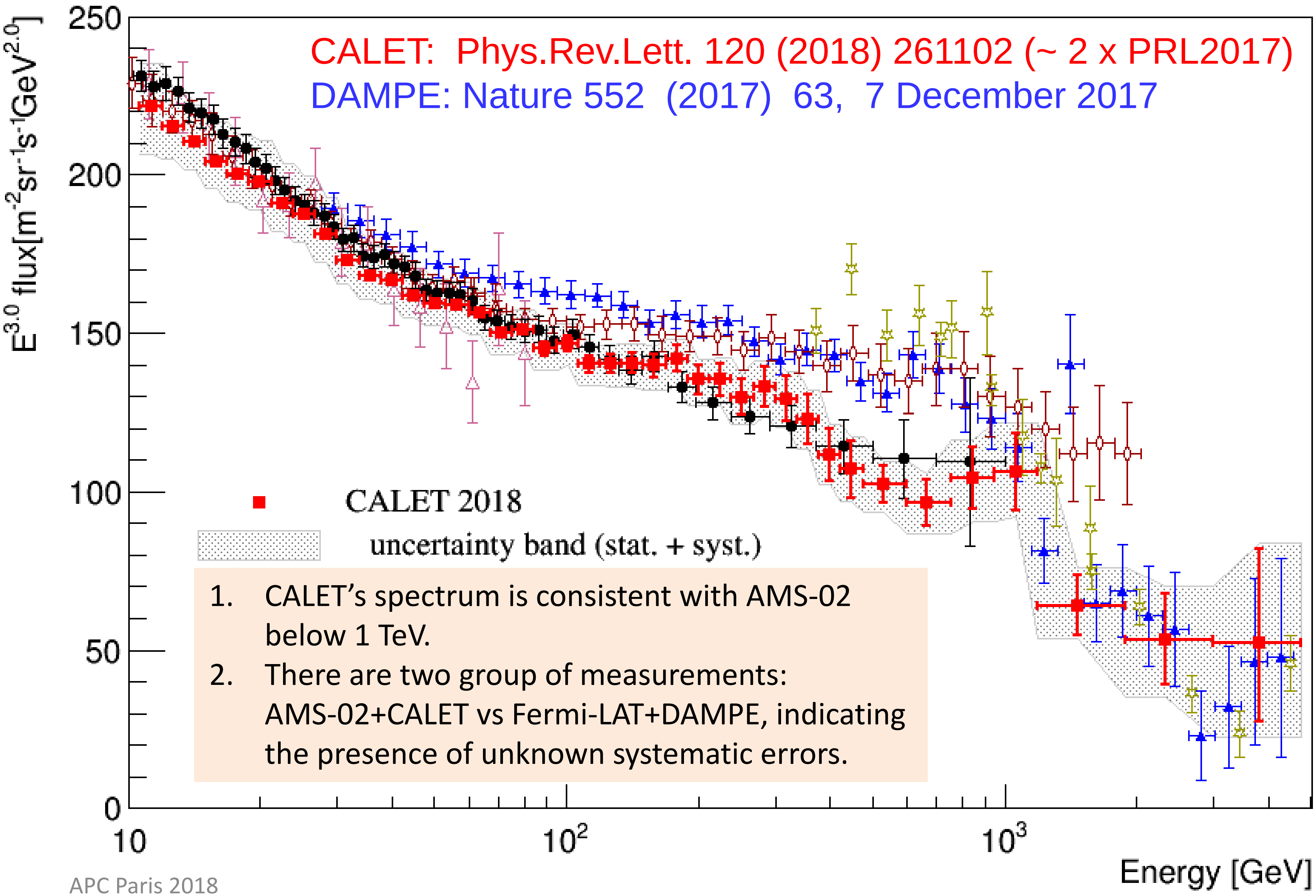
Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET



Extended Measurement by CALET

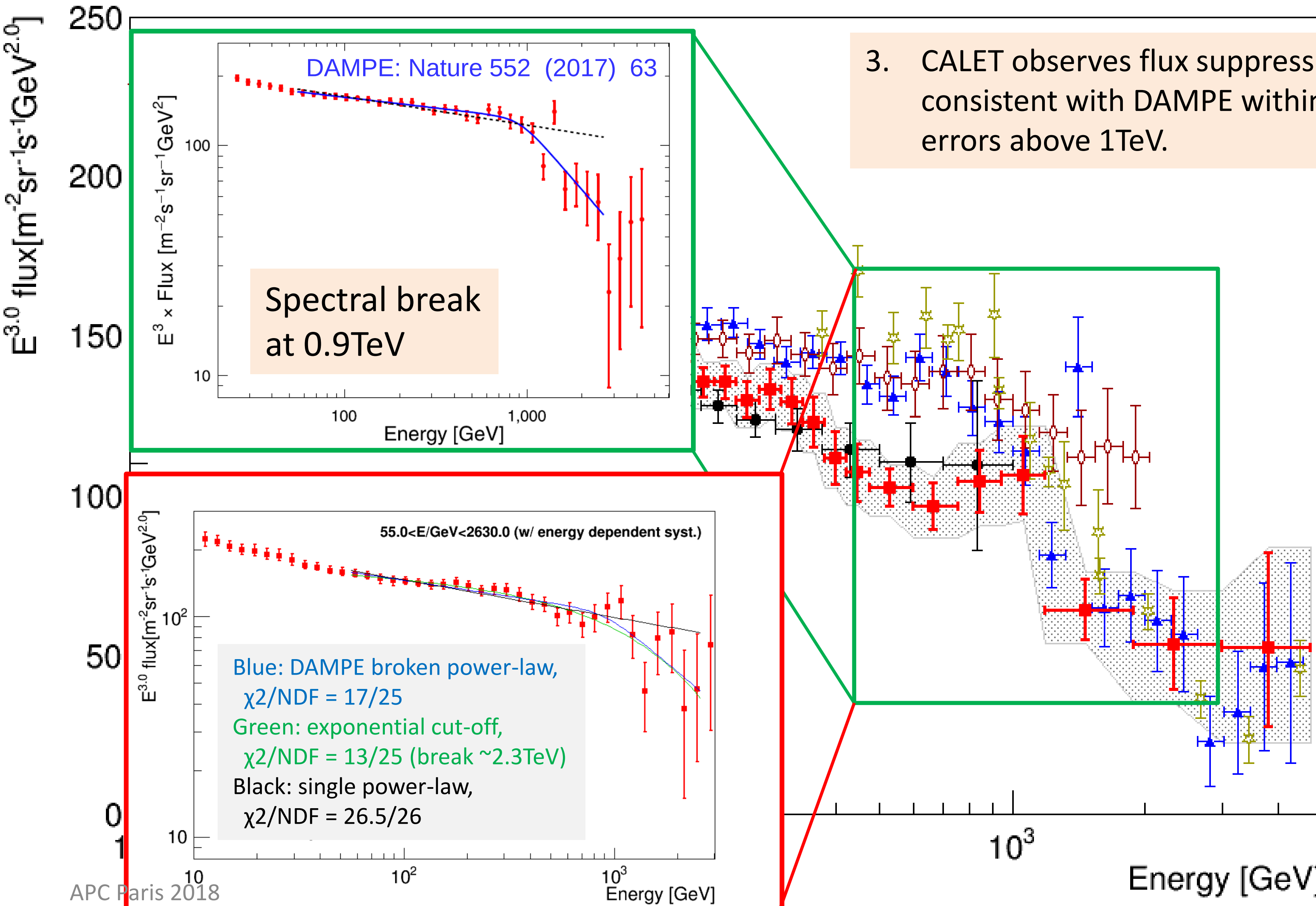
Approximately doubled statistics above 500GeV by using full acceptance of CALET



1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.

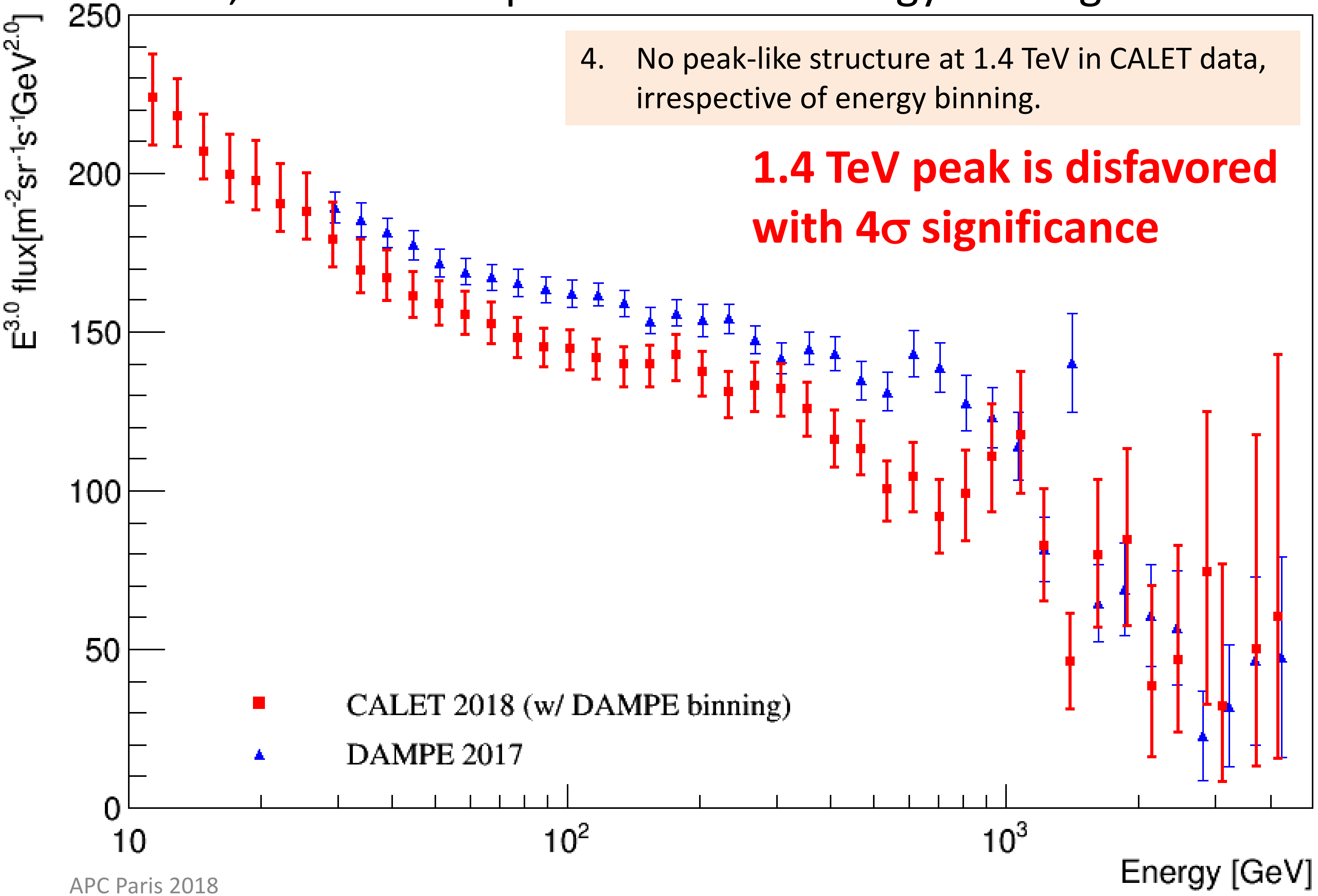
Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET



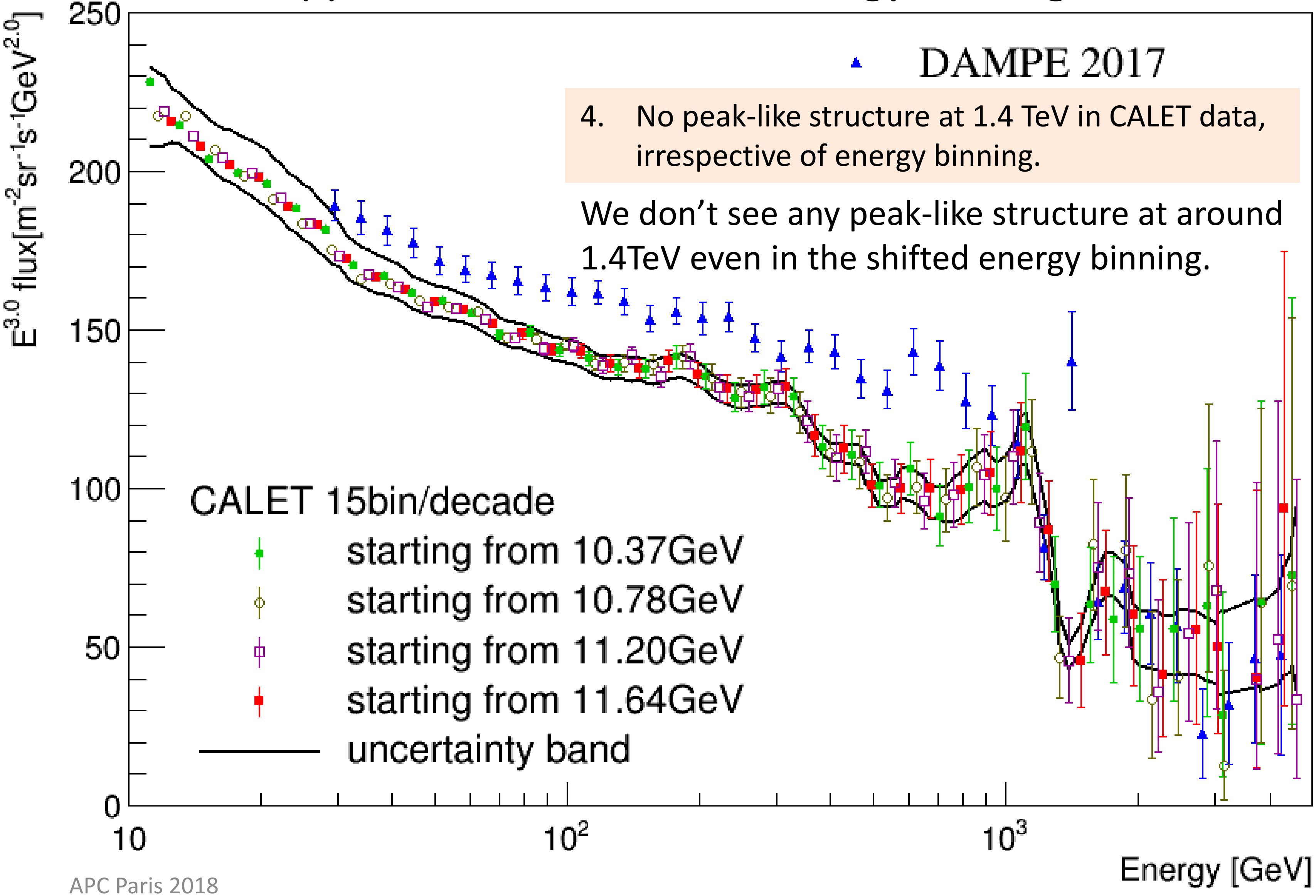
Comparison with DAMPE's result

Here, we have adopted the same energy binning as DAMPE.



Comparison with DAMPE's result

What happens if we shifted our energy binning…



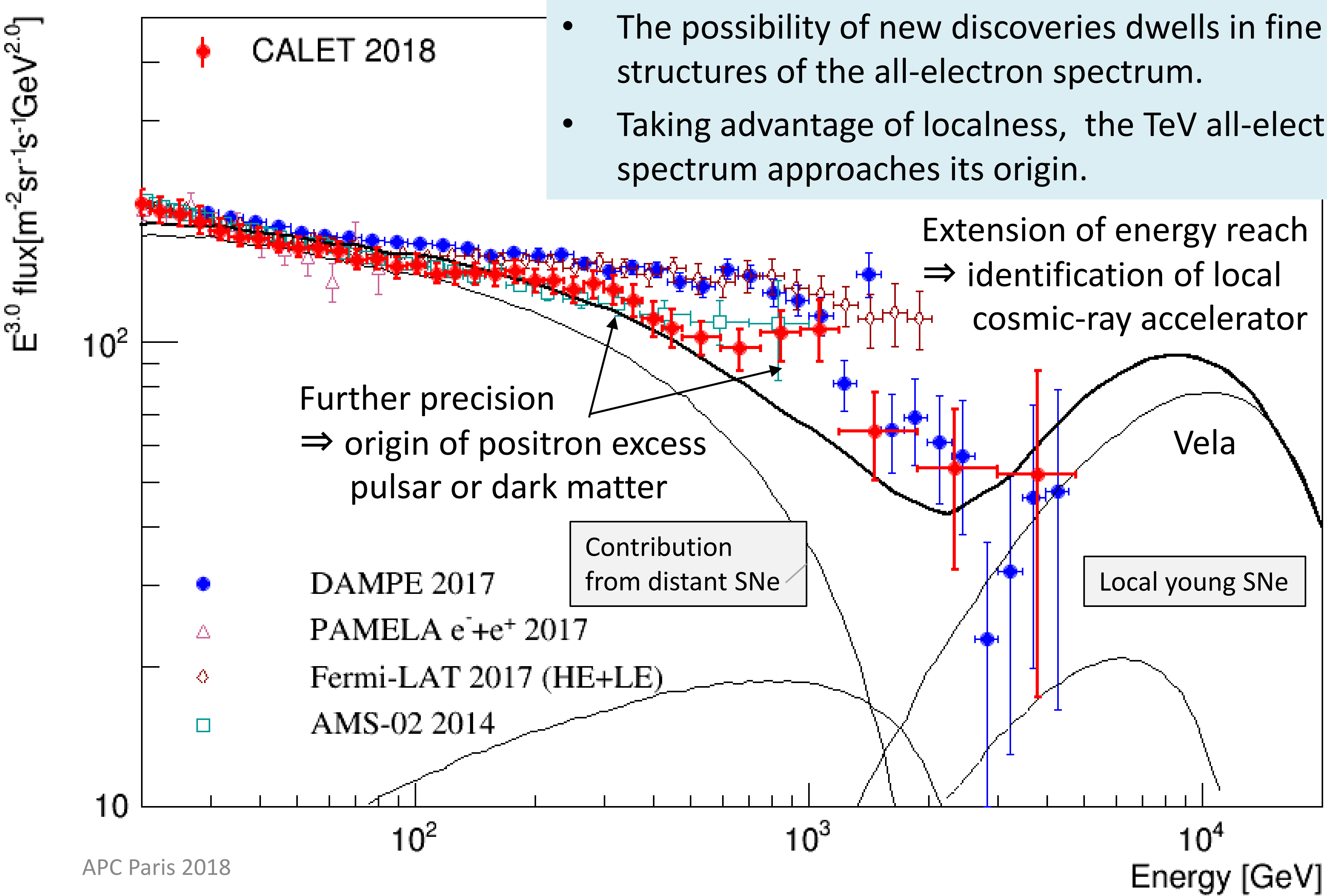
4. No peak-like structure at 1.4 TeV in CALET data, irrespective of energy binning.

We don't see any peak-like structure at around 1.4TeV even in the shifted energy binning.

Prospects for CALET All-Electron Spectrum

Five years or more observations ⇒ 3 times more statistics, reduction of systematic errors

- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of localness, the TeV all-electron spectrum approaches its origin.



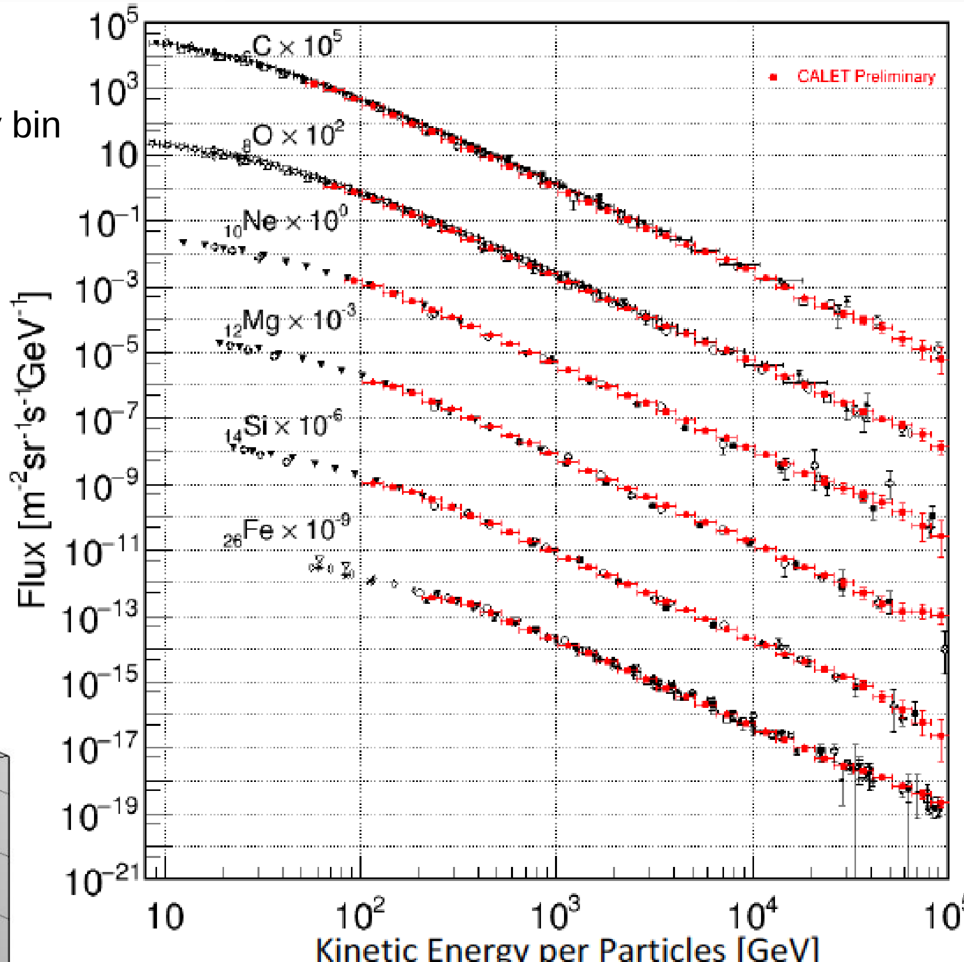
Preliminary Flux of Primary Components

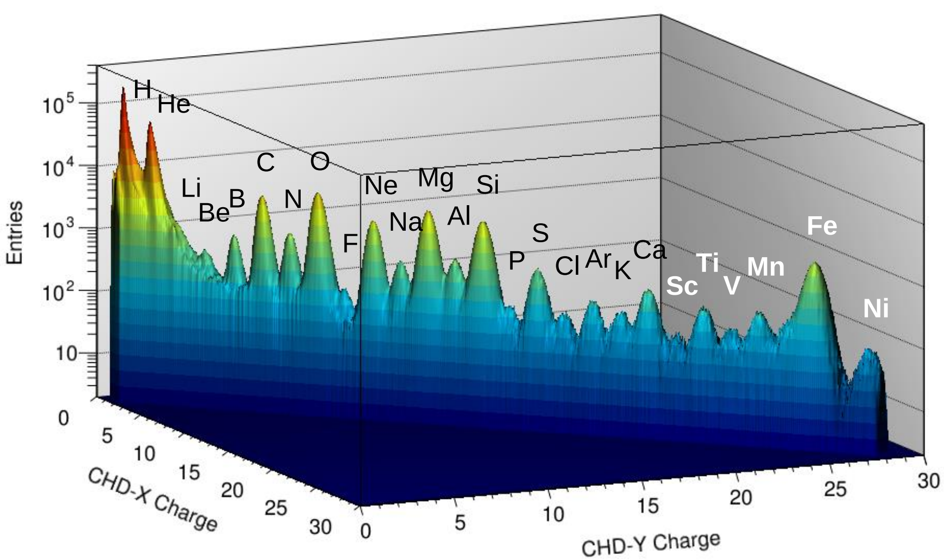
Flux measurement:

$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

N(*E*): Events in unfolded energy bin
SΩ : Geometrical acceptance
T : Live time
ε(*E*) : Efficiency
ΔE : Energy bin width

Observation period:
2015.10.13 – 2017.10.31 (750 days)
Selected events: ~13 million

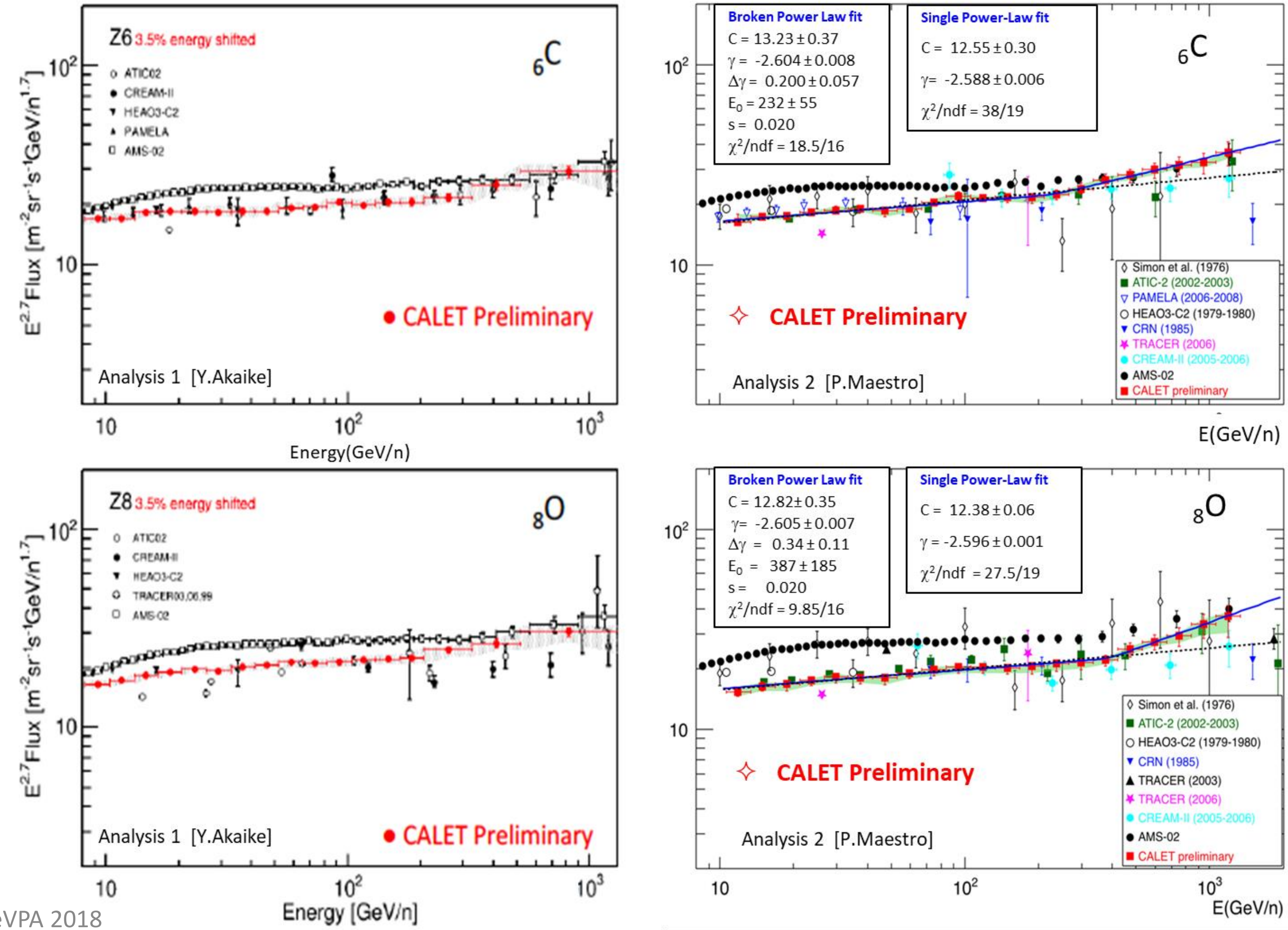




<u>Charge Separation only with CHD</u>
Clear separation of protons, helium to iron and nickel (up to Z=40).

Preliminary Energy Spectra of Carbon and Oxygen

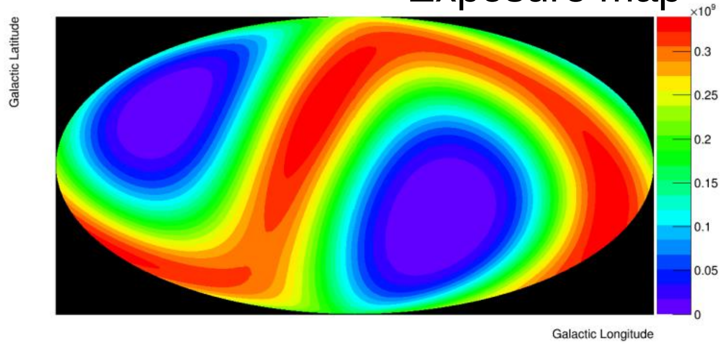
(2 independent CALET analyses)



CALET γ–ray Sky in LE (>1GeV) Trigger

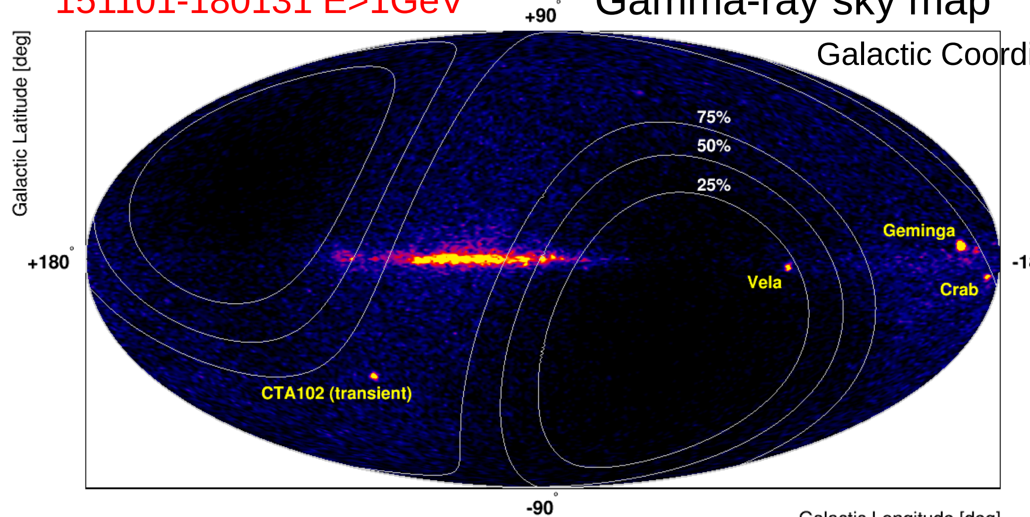
Analysis methodology:
N.Cannady, Y.Asaoka et al.
(CALET Collab.), ApJS 238 (2018) 5.

Exposure map



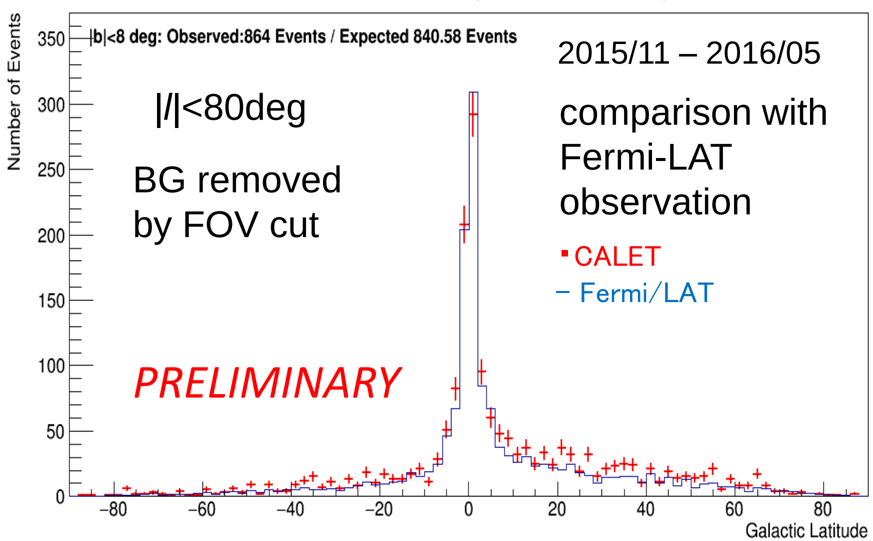
Gamma-ray sky map

151101-180131 E>1GeV

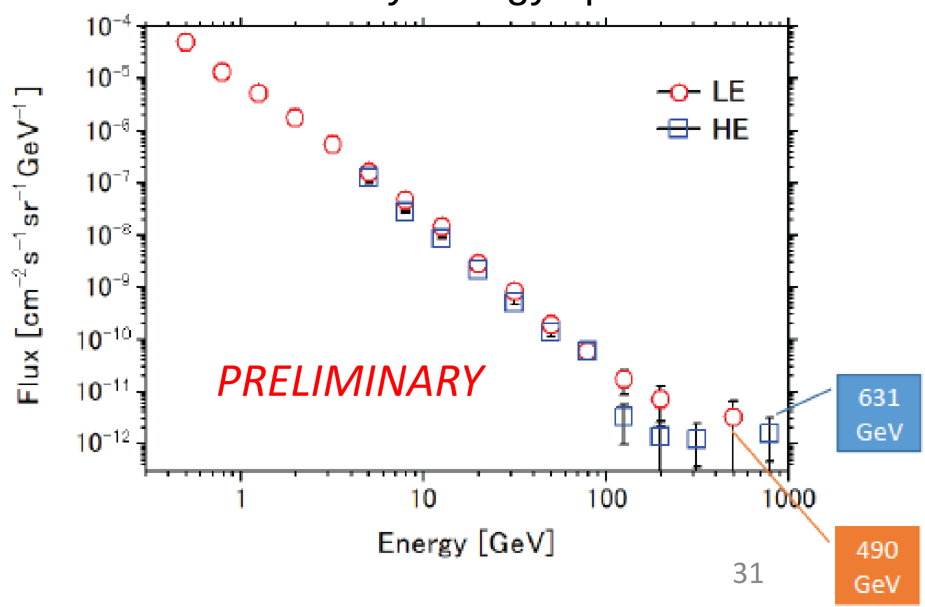


Geminga:432 Vela:138 Crab:150 All: 45740

Galactic diffuse gamma-rays



Gamma-ray energy spectrum



CALET UPPER LIMITS ON X-RAY AND GAMMA-RAY COUNTERPARTS OF GW 151226

Astrophysical Journal Letters 829:L20(5pp), 2016 September 20

The CGBM covered 32.5% and 49.1% of the GW 151226 sky localization probability in the 7 keV - 1 MeV and 40 keV - 20 MeV bands respectively. We place a 90% upper limit of 2×10^{-7} erg cm^{-2} s^{-1} in the 1 - 100 GeV band where CAL reaches 15% of the integrated LIGO probability (~1.1 sr). The CGBM 7 σ upper limits are 1.0×10^{-6} erg cm^{-2} s^{-1} (7-500 keV) and 1.8×10^{-6} erg cm^{-2} s^{-1} (50-1000 keV) for one second exposure. Those upper limits correspond to the luminosity of 3-5 $\times 10^{49}$ erg s^{-1} which is significantly lower than typical short GRBs.

CGBM light curve at the moment of the GW151226 event

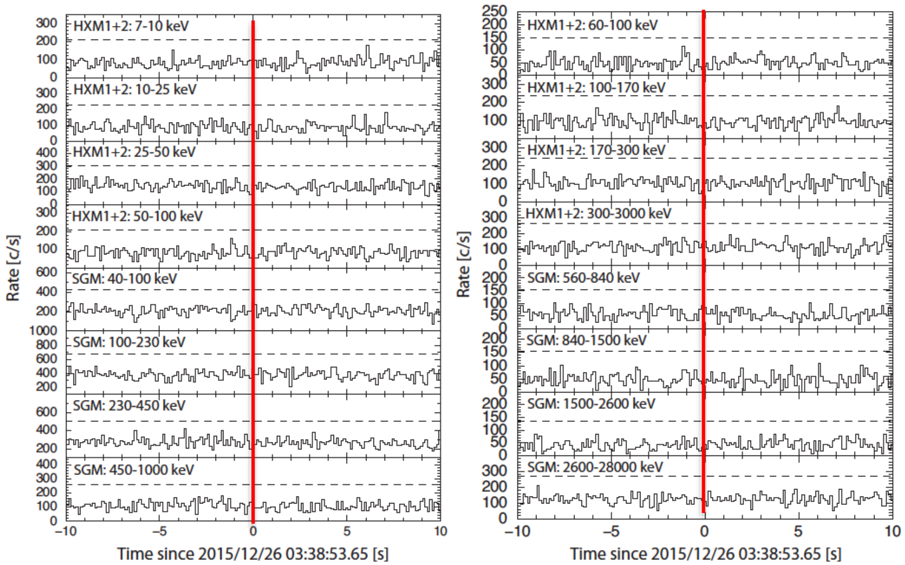


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

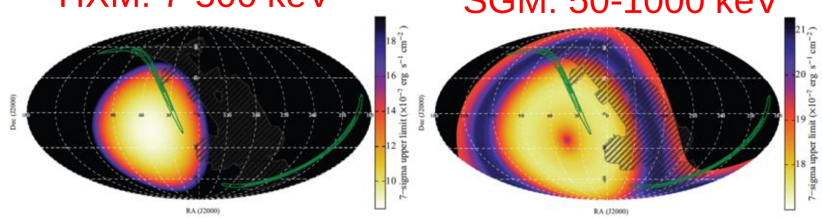


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating the upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV for SGM. The GW 151226 probability map is shown in green contours. The shadow of ISS is shown in black hatches.

Calorimeter: 1-100 GeV

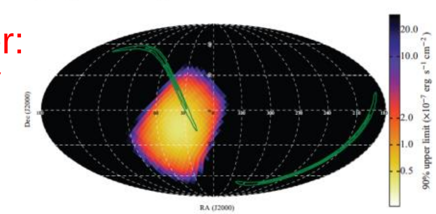


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of −2 is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

Updated analysis incl. all GW candidates in O2: O.Adriani et al. (CALET Collab.), ApJ 863 (2018) 160.

Summary and Future Prospects

- CALET was successfully launched on Aug. 19, 2015, and the detector is being very stable for observation since Oct. 13, 2015.
- As of May 31, 2018, total observation time is 962 days with live time fraction to total time close to 84%. Nearly 630 million events are collected with high energy (>10 GeV) trigger.
- Careful calibrations have been adopted by using "MIP" signals of the non-interacting p & He events, and the linearity in the energy measurements up to 10^6 MIPs is established by using observed events.
- All electron spectrum has been extended in statistics and in the energy range from 11 GeV to 4.8TeV. This result is published in PRL again on June 2018.
- The consistency between the CALET and AMS-02 all-electron spectrum is an important prerequisite for a study including the positron flux measurement by AMS-02.
- The accuracy and energy reach of our spectrum will improve by better statistics and a further reduction of the systematic errors based on the analysis of additional flight data during the ongoing five-year (or more) observation.